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TECHNICAL REPORT OCRE-TR-2018-004 Unclassified



Ocean, Coastal and River Engineering

The Canadian winter road infrastructure and climate change adaptation: **Prospective solutions through R&D**

Technical Report OCRE-TR-2018-004

Paul Dominique Barrette 1200 Montreal Rd, Ottawa, ON K1A 0R6

April 30, 2018



National Research Conseil national de recherches Canada





Ocean, Coastal and River Engineering

Génie océanique, côtier et fluvial

The Canadian winter road infrastructure and climate change adaptation: Prospective solutions through R&D

Technical Report UNCLASSIFIED

OCRE-TR-2018-004

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National Research Council Canada

Conseil national de recherches Canada

Ocean, Coastal and River Génie océanique, côtier et fluvial Engineering

The Canadian winter road infrastructure and climate change adaptation: Prospective solutions through R&D



Technical Report OCRE-TR-2018-004

Paul D. Barrette

April 30, 2018

[Frontispiece: Breakthrough of a snow plow on January 2011 in Northern Ontario [1]. Ice failure is attributed to a weaker ice cover.]

Executive Summary

In Canada, the cumulative length of the entire winter road network is estimated at 10,000 km. These are roads that are usable only in the winter – they run over land and across frozen water bodies (lakes, rivers and sea ice along coastlines and in bays). A large part of the challenge in managing that infrastructure stems from the extensive knowledge base that must be mobilized in order to gain a sufficient understanding of these roads. Unlike in the case of all-weather roads, nature provides winter roads with the foundation – frozen land and water surfaces –which needs to be trafficable and able to support the vehicles' weight. These surfaces are particularly sensitive to climate change. Socio-economic factors of northern communities – low density, isolated populations, distance to other infrastructures (hospitals, schools) and cold winter temperatures – need to be carefully considered, as they are not typical of southern locations.

Winter roads are, in general, managed either by local communities, provincial/territorial governments or the industrial sector (e.g. mines, energy). In all cases, they need to be well planned and regulated. They tie in with other transportation infrastructures, such as all-weather roads, rail and air strips. New platforms – airships and hovercrafts – are being evaluated.

Climate change may exacerbate issues that have traditionally affected over-land winter road operations, such as muskeg and permafrost. The main challenge for over-ice segments is the ice bearing capacity, either due to delays in achieving target ice thickness, or warmer ice. A large number of adaptation measures have been developed over the years, which can be applied at the planning, construction and maintenance stages, and for traffic management and access to ramps. These may be seen as a 'band-aid' approach – effective in many cases but insufficient to address the infrastructure as a whole and in the long term. For that purpose, increasing our basic knowledge base is required, which is done through research and development (R&D).

R&D is a process involving targeted investigations using standardized procedures, and meant to provide answers the specific questions on which information is lacking ('knowledge gaps'). They are typically conducted by research institutions and universities. R&D's ultimate outcome is new information, which may then feed into guidelines, standards and working practices.

Avenues of investigation proposed in this report include a means to characterize winter roads in a more systematic fashion, namely with a field tool incorporating a ground penetrating radar and other instruments. Documenting the roads in that fashion should be combined with all available data on goods and people transportation, i.e. physical information combined with all operational and logistical data (e.g. opening and closure dates, nature of goods transported) in an interactive database. It is therefore a promising and potent tool for capacity and multimodal planning. The outcome would be made available to stakeholders, namely operators, users and analysts in transportation logistics. Another prospective R&D investigation avenue is to address the integrity of floating ice segments. Several outstanding questions regarding the bearing capacity and deformational behavior of floating ice roads should be addressed. Topics that need to be investigated include: ice cover strength, how long a vehicle can be parked on the ice, how fast can a vehicle travel on the ice, how cracking patterns affect ice integrity, and what are the known procedures, techniques and technologies available to reinforce an ice cover. Answers to these questions would contribute to a safer usage of over-ice segments. These segments are very climate-sensitive, and a common weak link in an operation, causing delayed road opening at the beginning of the season, early closure at the end, and temporary closure mid-season. Also, the

consequences of breakthroughs can be significant – poorly designed or managed over-ice segments are a particular threat to life safety.

Drawing on these considerations, three recommendations are made: 1) The implementation of a system to gather data on road description and usage; 2) addressing the knowledge gaps outlined in this report; and 3) working toward nationally-consistent, more comprehensive winter road guidelines, incorporating new knowledge base.

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1 Introduction

In Canada, there are approximately 10,000 km of winter roads¹. These are roads that are usable only in the winter – they run over land and across frozen water bodies (lakes, rivers and sea ice along coastlines and in bays). They range in length from a few hundred meters to 100's of kilometers, and are managed either by local communities, provincial/territorial governments or the industrial sector (mines and energy). Winter road users rely on them for their yearly supply of fuel, construction material and other bulk commodities that are too expensive for air transportation. Winter roads are also used extensively for leisure activities such as ice fishing, snowmobiling and participation in sporting events (*e.g.* hockey tournaments, Dene hand games).

Warmer winters cause winter roads to close, leaving communities stranded or mining operations running out of supplies – airlifting is very expensive [2-4]. According to McDonald [5], "[f]lying supplies to the mines costs four to eight times more per pound than transporting them by road."

Climate change is thought to increase the frequency and extent of warm winters. As such, it affects the safety and effectiveness of this infrastructure and reduces its yearly operational lifespan. A reduction in the number of freezing-degree days (FDD)² is the most recognized concern. Both over-land and over-ice segments are affected. Contractors and engineering consultants have a wealth of knowledge and experience, and resort to various corrective measures to address the issues causing these closures. In parallel, as argued in the present report, there is a need for new Research and Development ('R&D') to improve our basic understanding of ice mechanics and hydraulics, which can be undertaken by research institutions such as the National Research Council and universities. The outcome of that R&D can then be used for input into manuals, standards and other such guidelines in the planning, design and usage of winter roads.

1.1 Objectives

The key objectives of this report are to provide:

- A summary of the Canadian winter road infrastructure as a whole, and various related aspects, namely construction, management and regulations.
- A brief definition/clarification of several notable concepts brought up by NRC during past discussions with INAC.
- A summary of the challenges that this infrastructure is currently facing in the context of climate change.
- An assessment of R&D investigation avenues that could be explored in moving forward with improving the effectiveness and safety of the winter road network.

A focus will be placed on segments over floating ice, for the following reasons:

- They are very climate-sensitive.
- They are common weak links in an operation, causing later road opening at the beginning of the season, early closure at the end, and temporary closure mid-season.
- The consequences of breakthroughs can be significant poorly designed or managed over-ice segments are a particular threat to life safety.

¹ This is a rough approximation which may be seen as an upper limit – about 8000 km are officially recognized, plus an estimated 2000 km of industrial and community-based operations and sea ice roads. ² This is the average number of degrees below freezing point summed over the total number of days in a given time period. For instance, if the average air temperature on day 1, 2 and 3 was -5°C, -8°C and -12°C, respectively, the number of FDD for these three days is 25°C (5+8+12).

This report is written mostly from a science and engineering perspective (as opposed to sociological or economic). But this is done at a high level – the more technical material is confined to appendices – with abundant referencing where appropriate, in case the reader wishes to learn more about any particular topic.

1.2 Methodology

This report is the outcome of a desktop study. The information enclosed is based on NRC's knowledge base in the properties, mechanics and hydraulics of river and lake ice, as well as soil mechanics and permafrost engineering. It also draws on the NRC's publication archives, the Federal Science Library, an in-house ice engineering documentation center, as well as Internet search results.

No information is 100% reliable. Even technical papers and reports, including this one, are affected to some extent by author biases, pre-conceived ideas and oversights. Articles published in scientific and engineering journals are normally peer-reviewed, i.e. submitted manuscripts are critically assessed by third-party experts. Conference proceedings papers and reports are not usually peer-reviewed, or they are but less stringently – they may have been reviewed internally (within the author's organization). Information found on the Internet varies significantly in quality and reliability. Newscasts by reputable organizations (e.g. CBC) are deemed trustworthy.

2 The winter road infrastructure

In this section, some background information is provided on a number of aspects related with winter roads, namely the nature of the infrastructure, what these roads are, how they are planned and built, an outline of the regulations, and how these roads relate with other transportation platforms.

2.1 Three governing elements

To better understand the challenges associated with winter roads, it helps to be aware of what is involved to make that infrastructure successful. In Figure 1, it is depicted conceptually as being at a junction between three basic, independent elements: Nature, Society, and Science & Engineering.

2.1.1 Nature

Nature includes weather (temperature, wind and precipitations), foundation (soil, rock, permafrost, etc.), hydrological processes, geography and fauna and flora. Natural reserves are an example of an infrastructure – this infrastructure is mostly concerned with Nature. Winter roads are much more dependent on that element than are all-weather roads (i.e. city streets and highways, gravel and paved country roads). This is explained below.

2.1.1.1 Foundations

Foundations are what lie below the road. Unlike for all-weather roads, the foundations for winter roads are not engineered – operators use what nature provides them with. The surface can be modified (e.g. surface flooding) and freezing can be promoted (e.g. by packing the snow), but there is no other control on ground type (rock, soil, etc.). Depth of frozen ground and ice thickness are mainly of function of air temperature. However, a well thought-out route will allow terrain optimization, for instance, by avoiding south-facing slopes (more prone to melting due to sun rays),m lake areas where nearby streams are known to affect the ice thickness, or muskeg.

2.1.1.2 Topography and surface conditions

Motor vehicles have a wide radius of curvature, low clearance and limited traction. As a result, they require a wide right-of-way, shallow grades and relatively smooth surfaces. In fact, all-weather road designs are based on such limitations. For example, a considerable amount of funding is provided to reduce grades, notably through the extensive usage of heavy machinery, excavation tools and dynamite. Smooth surfaces are produced (i.e. pot holes are objectionable), such as asphalt, concrete and graded gravel. For winter roads, frozen ice covers do provide a flat and smooth surface, but this type of support for over-land segments is generally not available.

2.1.1.3 Air temperature

This is a decisive factor, since it controls extent and timing of freezing conditions.

2.1.1.4 Snowfall

Because of the limited amount of clearance, motor vehicles are vulnerable to any snow accumulation. While cities and highways benefit from highly effective winter maintenance equipment, that is not the case for winter roads, many of which are at remote locations and may not have the same level of financial and logistical support.

2.1.2 Society

This is an intricate and complex mixture of many tangibles and intangibles, e.g. economics, community living, access to health care, employment, public/private services. Schools are an

example of an infrastructure that is mostly concerned with that element. Parameters of interest in that case include population density, location, demographics, public access, governance, religious affiliation and security. Some of these factors come into play for winter roads as they do for all-weather roads.



Figure 1: The winter road infrastructure is at a crossroad between three basic, independent elements. See text for explanations.



Figure 2: Factors affecting winter road safety can be similar to those from other road types – this example is from Manitoba³, and appears to be related to drinking and driving.

An example of a societal challenge is shown in Figure 2 – see also information contained in IBI Group [6]. Furthermore, an activity increase in the North is related with the development of new

³ http://www.cbc.ca/news/canada/manitoba/drunk-driving-charges-laid-after-crash-on-winter-road-1.1256299

resources (e.g. in the mining sector), community expansion and the opening of the northern seaway during part of the year. In Northern Ontario, for instance, the indigenous communities have strong population growth rates [6]. From that perspective, unless solutions to climate change effects can be found, winter road operators will have to do more with less in a foreseeable future.

2.1.3 Science and Engineering

For the purpose of this report, we will define science as knowledge of the behavior and physics of materials (solid, liquid, gas); engineering includes new operational methods, procedures and tools. Infrastructures that strictly involves the Science & Engineering element are rare – examples include astronomical observatories and particle colliders. Both study nature, but their design, conception, usage and maintenance is mostly independent of it. They are also mostly independent of society – parameters such as those that matter for schools (as listed earlier) are not a significant factor.

For winter roads, Science and Engineering is the knowledge required to plan, build, maintain and manage an operation. This is a function of budgetary constraints, and contributes significantly to the difference between an operation that is safe and effective and one that is less so. An understanding of the winter road infrastructure has to draw from several areas of expertise, including:

- Geotechnical engineering
- Ice hydraulics
- Mechanical engineering
- Environmental sciences
- Climate studies and physics of the atmosphere

Compared to all-weather roads and to other infrastructures, winter roads are not well understood. The reason for this is debatable. One important contributing factor could be the fact that, as mentioned above, a winter road is primarily nature's creation. Unlike in the case of all-weather roads, it is nature, not humans, that provides winter roads with foundations – frozen land and water surfaces – that need to be trafficable. Another contributing factor is the number of studies done on winter roads, which is a small fraction of the number of those done on other infrastructures.

2.2 Winter roads – A brief overview

A winter road typically consists of segments that run over land and on floating ice surfaces (Figure 3). Each type comes with its own challenges in terms of planning, construction and safety. The over-land segments are underlain by soil that is frozen to a given depth, referred to as the 'sub-grade', itself underlain by bedrock, or permafrost at higher latitudes. The sub-grade can be overlain by snow or artificially-produced ice, used as a supporting surface and as a protection to the underlying vegetation. That ice may be produced with water tankers or from water pulled out directly from a nearby pond or lake. To increase thickness, water can be used to flood ice chips, to help increase ice buildup. The required thickness of that ice/snow layer depends on vehicle weight, weight distribution and frequency of passages.



Figure 3: Simplified diagrams of an over-land (left) and over-ice (right) segments of a winter road.

Segments running on floating ice take advantage of that material, which is naturally-available and leaves no environmental footprints upon melting in the spring. An ice cover is able to support a load because of the ice cover's buoyancy and its resistance to flexure.

What controls the yearly operational lifespan, i.e. the parameters involved in road opening and closure, need to be carefully addressed, especially the weak links. For additional information, the reader is referred to Proskin et al. [7], itself based on Adam [8] and other guidelines [9-13]. Systematic comparisons between some of these guidelines are also available [6, 7, 14, 15].

2.2.1 Road opening and closure

Road opening is usually a function of the time required to grow a safe ice thickness, which itself depends on the maximum expected weight (e.g. some roads are meant to carry tractor trailers, other to only handle light vehicles). For over-ice segments, this is often achieved in two steps:

- The first step is removing the snow layer from the ice, so as to accelerate ice growth [snow acts as an insulator e.g. 16, 17]. This is done with light vehicles, once a safe thickness for these vehicles is achieved. Note that for over-land segments, the snow is left in place, so as to preserve a high albedo⁴ it is compacted, thereby also reducing its insulating effects, which accelerates ground freezing.
- The second step is flooding the surface with water, or using spray ice, to artificially increase the thickness to the required target level (Figure 4).

Understandably, an optimum number of FDD at the beginning of the winter will favor an earlier opening – a well-explained example is provided by Hori et al. [18] for the James Bay Winter Road in Northern Ontario.

⁴ Albedo in this context is the amount of sunlight reflected by the ice/snow. If the ice/snow surface becomes dirty, for instance when it incorporates sand, it absorbs the sunlight, which accelerates melting because of stored heat.



Figure 4: Ice cover thickening may be conducted using a pump to flood the ice (left) [19] or implementing a spray ice system (right)⁵.

Figure 5 shows snow cat vehicles leading the way to a February 8 opening in 2018 of the Tibbitt to Contwoyto Winter Road (TCWR). That is the road supplying the diamond mining industry in the NWT [20-23]. That road is also used extensively by the local communities for their own purposes.

Official road closure is when an operation ceases its activities. This varies from year to year – an example is shown in Figure 6. Road closure can be due to the deterioration of the over-land segments and its transition to the over-ice segments, for example, where the road is darkened by the soil. Because of the lower albedo, sun rays are absorbed, contributing to the increased melting. Softening of the over-ice surfaces can also be a factor, as it eventually impedes trafficability. Temporary road closure may also happen during the season, when a weak link becomes unusable and a diversion is not possible. Each winter road operation is different and there can be a number of factors contributing to a late opening, mid-season or end-of-season closure. Some operators may close their road because there is no longer a use for it.



Figure 5: Snow cat plowing machine are preparing the large TCWR winter road operation for opening (February 2018).⁶

⁵ http://www.cbc.ca/news/canada/north/yukon-river-ice-bridge-spray-suspended-1.4500692

⁶ http://www.cbc.ca/news/canada/north/tibbitt-road-opens-2018-1.4515200?cmp=rss



Figure 6: Historical closure dates of the Tuktoyaktuk-Inuvik winter road, showing a slight progression toward an earlier closure [24]. Note that this road has recently been replaced with an all-weather road.

2.2.2 Types of winter roads

Table 1 provides an example of a classification for winter roads [7]. It should be pointed out, however, that the terminology used by winter road stakeholders is not uniform. For instance, 'ice road' and 'ice bridge' are often used to designate a winter road segment on floating ice [e.g. 8].

The information in the following section is from Proskin et al. [7].

2.2.2.1 Compacted snow road (C1)

This is natural snow that has been compacted enough to allow trafficability – it is the least expensive road. Compaction is done in various ways, notably with rollers and steel frame drags. They have limitations in terms of loads (less than 40 tons) and frequency (less than 1000 passages). In the years where snow fall is lower than usual, additional snow may be hauled from nearby locations. C1 roads are vulnerable to warm temperature and exposure to sunlight.

2.2.2.2 Over-land ice-capped snow road (C2)

C2 roads involve surface flooding and allow for the passage of heavier vehicles than C1 roads. The reason is that an icy surface is stronger and more resistant to wear than a snow surface. In places, the sub-grade can be directly overlain with that ice layer (i.e. without a snow layer). However, adding water to the compacted snow complicates the logistics – water tankers or trucks have to be involved and nearby sources of water have to be available. The operators may require permission from environmental authorities to use that water. Lower traction on C2 roads has to be taken into account in road planning, for instance when considering grades and vehicle capabilities.

Terrain	Road type	Category	Description
Over-land	Compacted snow roads	C1	Road surface composed of compacted natural snow
	Ice-capped snow roads	C2	Compacted natural snow that is ice capped using water
	Aggregate ice roads	C3	Building ice surfaces by flooding with water or harvesting and flooding ice chips (aggregate)
Over-ice	Floating ice road	C4	Roads that follow floating ice covers on lakes or rivers
	Grounded ice road	C5	Roads that follow ice covers grounded on a lake or river bottom

2.2.2.3 Over-land aggregate ice roads (C3)

Over-land aggregate ice roads will accommodate the highest vehicle weights and passage frequency, and are suitable to uneven terrains. An additional step in building them is the recourse to ice chips that are flooded with water. The road builder makes use of tractors equipped with rippers. The ice is hauled and dumped at the location (as would be done with gravel for an all-weather road). The ice chip surface is then packed and saturated with water. This accelerates the rate of sub-grade thickening where it is required. C3 roads do not need a snow layer. Logistically, they are even more involved than C2 because they rely on the availability of water and ice, and may require permission from environmental authorities to access both.

2.2.2.4 Floating ice road (C4)

Frozen water surfaces are clearly a very practical medium for surface transportation. They are flat, require minimum maintenance and may run in a straight line (as opposed to over-land segments, which have to take into account topography and vegetation). The limiting factor is climate, mainly the air temperature (the number freezing-degree days – FDD) and amount of snow fall, since these factors are controlling the rate of ice growth. Human intervention can help increase that rate, i.e. by removing the snow cover, and thickening by flooding or spraying water over the ice surface. The consequences of a breakthrough in C4 roads remain a concern for winter road operators. Risk mitigation measures include adequate traffic management, ice thickness and quality.

2.2.2.5 Grounded ice road (C5)

Grounded ice roads lie directly on the river or lake bed, typically near the shorelines. The ice can be fastened to the bottom. Alternatively, at shoals (i.e. in shallow lake areas), and where the ice cover has been thickened to a sufficient extent by surface flooding, the ice can sink down and end up resting on the lake's bottom. C5 roads are generally capable of supporting higher loads than C4 roads.

2.2.3 Planning the road

The following also draws from Proskin et al. [7].

2.2.3.1 Defining road requirements

These requirements are as follows:

- Schedule and operating windows: What are the target road opening and closure dates.
- *Traffic type and volume*: What kind of vehicles (weight, size, axel load distribution) and how many passages are expected.
- *Road right-of-way*: This is the road width requirements vary with road type, number of lanes, location, type of work involved (servicing communities, mines, seismic program,...).
- Environmental and regulatory requirements: See section 2.2.6.

2.2.3.2 Developing route options

- *Over-land options*: This takes into account topography, water and snow requirements and the nature of the terrain (e.g. dry mineral soil is desirable; muskeg is not see section 3.2.1).
- *Over-ice options*: Parameters to be considered are currents (if any), availability of portages and bathymetry, and water influx from nearby streams. Shallow areas and shoals can be objectionable, for instance, to address issues related with vehicle speed (see section 5.3.2.3).

2.2.3.3 Weather parameters

- *Temperature and snow fall for over-land segments*: Historical records of freezing-degree days and snow fall are critical parameters Proskin et al. [7] mention 300°C-days as a minimum for ground freezing, and 5-10 cm of snow to support traffic.
- *Ice conditions*: Similarly, historical ice thickness data should be consulted, along with freeze-up dates and ice cover disintegration/break-up dates.
- *Climate change*: A handle on warming trends is also helpful to try to anticipate the expected number of FDD.

2.2.4 Physical characterization of a winter road

The physical nature of a winter road is highly variable. For overland segments, the parameters of interest include the following:

- Foundation soil, solid rock, gravel, muskeg, icy surface, permafrost.
- Routing characterization width, itinerary, radius of turns, grade, cross slope, slope direction, vegetation (e.g. shade vs no shade), creeks, obstacles (e.g. boulders, large trees).

For over-ice segments:

- Foundation Floating or grounded ice, length of segment.
- Hydrological River versus lake, currents.
- Ice thickness This can be done by regular measurements or on continuous mode (profiling).
- Ice cover Lake ice versus columnar-grained ice, white ice versus blue ice⁷, pressure ridges, cracks.

⁷ Or 'black ice' or 'clear ice' – very low in 'air bubbles' compared to white ice.

• Routing characterization – Width, radius of turn, angle with shoreline.

For the winter road as a whole:

- Length Over-land versus over-ice.
- Structural bridges Number, size, type, capacity.
- Snow coverage Thickness and extent (including bare segments).
- Usage One-way versus two-way, nature of traffic, cargo vs people transportation.
- Type of vehicles Weight, clearance, turning radius.
- Logistics Weight stations, meteorological instrumentation, rest stations, gas pumps.

These parameters are useful for the purpose of road planning and usage. Not all operations collect that information – means of obtaining it will be discussed later.

2.2.5 Winter road management

Winter road management structures in Canada fall roughly into three main categories (Table 2). The following is a brief description of each, based on the author's consultation with a large number of stakeholders. This is a preliminary assessment; it is mostly qualitative – a systematic analysis with supporting data has yet to be compiled.

2.2.5.1 Provincial/Territorial

These roads are built and maintained by the government (namely Ontario, Manitoba, Saskatchewan, NWT), with support from engineering consultants. They generally abide by standard procedures for the construction, maintenance procedures and quality assurance, including monitoring of vehicle weights and ice thickness (for C4 and C5 segments).

	Province or Territory	Local communities	Industrial sector
Level of funding	Medium to high	Low to medium	Medium to high
Users	Community members, supply commercial vehicles	Community members, supply vehicles	Commercial vehicles
Main road types	C1 to C5	C1, C4	C1 to C5
Yearly operational lifespan	As long as possible	As long as possible	Enough loads to supply required material
Main vehicle types	All types of vehicles	Automobiles, light trucks and snowmobiles	Trucks of all sizes, from pickups to tractor trailers.
Main distribution ^(*)	NWT, Manitoba, Saskatchewan	Ontario, Quebec, Newfoundland and Labrador	Country-wide

 Table 2: Differences in winter road management structures.

^(*)Other provinces or territories not listed here have very few winter roads.



Figure 7: The Hudson-Oka operation, owned by the Léger brothers – it is one of the three ice bridges crossing the Ottawa River between Ottawa and Montreal.

2.2.5.2 Local communities

These roads service community needs: access to work, school, health care, air strips, fishing and hunting grounds, leisure activities. Included are privately-owned ice bridges, an example of which is shown in Figure 7. Operations run by local communities may not be as consistent as those managed by governments and the industrial sector in terms of construction and maintenance procedures, rules-of-the-road and safety monitoring. Also, communities may or may not have the required funding or resources to fix or accommodate critical problems causing road closure.

2.2.5.3 Industrial sector

These roads, which include heavy duty industrial operations, are independently funded by the private sector, notably mining and hydro power companies. They are typically, though not always, for industrial usage, i.e. up to very heavy loads (40+ tonnes), for which in-depth analysis of load distribution (e.g. for axle spacing) and ice bearing capacity (on C4 and C5 road segments) is often conducted by specialized engineering and geophysical firms. According to [7, p. 91], "Industrial winter roads will have more stringent requirements due to higher traffic loads and volumes, and have a higher level of monitoring and control that better assesses and meets risk management objectives".

2.2.6 Regulations and permitting

As stated in Proskin et al. [7, p. 99], "[v]arious national, provincial, and territorial regulations apply to the construction, operation, and monitoring of a winter road, [many of which were] developed to mitigate negative environmental impacts on land and water". Land use permits, issued by the federal government, include requirements, such as minimum snow cover, frost depth and the maximum amount of water that can be extracted from lakes and streams. For instance, Fisheries and Oceans Canada is concerned with developments affecting freshwater habitats. Examples of provincial and territorial requirements may include timber permits and water licenses.

For road usage in Ontario, the regulations of Ontario Highway Traffic Act apply – they are enforced by the Ontario Provincial Police [6]. There are currently no requirements for work permits when constructing a winter road. But for realignment, information (routing, mapping, archeological sites) is to be provided to the Ontario Ministry of Natural Resources and Forestry. Work permits are also required for new water crossings. Issuing of these permits is done in consultation with the local communities. Also, "[u]nder the Far North Act, 2010, most development in the Far North of Ontario, including all-weather transportation infrastructure, is prohibited from proceeding in advance of a jointly approved community based land use plan for the area, unless an order is made to except or exempt an individual project. Where a community based land use plan is in effect, development must be consistent with the direction contained in the approved plan." [6, p. 26]

Depending on the jurisdiction, factors that can be an issue for over-ice segments include [7]:

- Excessive sediment deposition related with the existence of a winter road. Means of protection include mitigation of soil erosion by ensuring stream banks have a shallow slope.
- The presence of an ice bridge crossing a river, which may impede or modify the flow of water below it.
- The extent to which fish habitats may be affected by the ice road.

For over-land segments, again depending on the jurisdiction, factors to be considered include:

- The volume of water needed for an ice-capped C2 or C3 road a given threshold (e.g. 10%) and a minimum water depth (e.g. 1.5 m) may be stipulated.
- Terrain stability a dry, frost-stable soil is preferred.
- Grades the steeper the terrain, the more soil erosion. Higher grades promote soil erosion.
- Permafrost (where it occurs), which is sensitive and should be used with caution.
- The ground should be frozen to a minimum depth with a minimum snow cover thickness (to protect the vegetation).
- Machinery should be used in a way that will not damage the terrain, for instance, by keeping bulldozer blades off the ground.
- Snow windrows should not be continuous they should have gaps, so as to allow the passage of wildlife (while also allowing meltwater to drain better in the spring).

Issues to address for road closure include:

- Removal of equipment and debris.
- Ice bridge dismantling, so as to allow the river to flow freely when its cover begins to break-up in the spring.
- A proper abandonment plan.

In Manitoba, as stated in Government of Manitoba [25, p. 33], "[a]n Environment Act Proposal Form must be filed before any construction is started on any new roads". In that document [25], anyone involved in an accident during transportation of a contaminant is referred to the Federal Transportation of Dangerous Goods Act, and to the Manitoba Environment and Safety and Health. Included in the definition of 'contaminant' are:

- Spills, leaks or fires involving chemicals such as pesticides or fertilizers.
- Radioactive material.
- Petroleum spills over 100 liters.

In Saskatchewan, "[a]n Environmental Assessment Approval must be obtained before any construction is started on any new overland road locations" [10, p. 33]. Anyone involved in an accident during transportation of a contaminant is referred to the Federal Transportation of Dangerous Goods Act. All environmental accidents are to be reported to the Spill Control Center. Contaminants are defined the same way as in Manitoba.

The above provide an idea of what may need to be considered, depending on the nature and location of the winter road operation.

2.2.7 Multimodal transportation

Multimodal transportation refers to the ability for people and goods to circulate across various transportation platforms – air, rail, road and marine⁸. In Canada, the winter road infrastructure is part of that network. For instance, amongst its currently proposed objectives, Ontario's Northern Ontario Multimodal Transportation Strategy (NOMTS)⁹ includes improving access to and by remote communities and by northern industries, enhancing linkages to Southern Ontario and improving the safety of the network.

Multimodal transportation plays a key role in winter road planning and usage, as there are connections between these roads, all-weather roads, air strips and railways. Also, alternatives (typically, air strips) are critical to northern communities when a winter road becomes inoperative, for instance, to plan important supplies to be flown in. The transition between moving in and out of the winter road operational window also affects planning. Furthermore, the availability of alternative platforms needs to be considered in the medium to long term planning of a winter road network. Airships to supply northern communities, discussed further down, would be an additional transportation mode.

For an overall Canadian perspective on multimodal transportation, the reader is referred to [26].

2.2.8 Prospective new platforms

2.2.8.1 Airships

Airships (Figure 8), also called dirigible, have been in existence for about 150 years¹⁰. This aircraft is essentially a self-propelled balloon filled with a gas whose density is lower than that of air – historically, this gas has been either hydrogen, later replaced by the helium which is non-flammable. Airships have been used by the German and British military during World War I, then for passenger transport until the 1930's. Although they have been since superseded by fixed-wing aircrafts and helicopters for air transportation, soft shell helium-filled airships (known as 'blimps') are still being used for scientific and military purposes; they are also a well-known marketing tool. Airships are often designated as being 'hybrid', alluding to their dual lifting capacity – that is provided 1) by the lower density gas and 2) by the aerodynamic lift of an airplane.

⁸ <u>https://northernontariommts.files.wordpress.com/2017/07/draft-northern-ontario-multimodal-transportation-strategy-executive-summary1.pdf</u>

⁹ <u>https://nomts.ca/discussion-paper/#C1A</u>

¹⁰ https://www.britannica.com/technology/airship



Figure 8: An airship designed by Lockheed Martin Corp., which is being considered to supply mining operations in Northern Quebec.¹¹ Approximate length is 100 m, 20-ton capacity and cruising speed of 115 km/h.¹²

There is currently a resurgence of interest for this platform. The viability of cargo and passenger airships as an alternative or complementary transportation platform to supply northern communities has been investigated, notably in Northern Quebec¹³, Eastern Manitoba and North-West Ontario [27] and between Churchill and Rankin Inlet¹⁴. Although winter roads are still considered the most cost-effective option, this may not be the case for large tonnages (Figure 9).¹⁵ In that analysis, applied to a prospective connection between Rankin Inlet and Churchill, the cost for the initial build and yearly builds are \$25M and \$12M, respectively. Truck rates are 2.5 times that of those for all-weather roads – they are assumed to be \$0.32 per tonne-kilometer, assuming an empty return. The yearly fixed cost per proposed airship is \$8.3M, with about \$3M to build a hangar. Cost per trip is assumed to be about \$8k.

Combining airships with winter roads is also deemed a promising alternative [27]. According to Hori and Gough [28], Airbus Industries currently has a 40-tonne capacity prototype, with a \$40M price tag per unit (compared to \$75M for a A318)¹⁶.

 $^{^{11}\} http://business.financialpost.com/transportation/no-roads-no-problem-how-blimps-could-help-northern-quebecs-miners-overcome-their-infrastructure-woes$

¹² http://www.cbc.ca/news/canada/north/lockheed-martin-airships-1.3524549

¹³ http://business.financialpost.com/transportation/no-roads-no-problem-how-blimps-could-helpnorthern-quebecs-miners-overcome-their-infrastructure-woes

¹⁴ https://www.winnipegfreepress.com/opinion/analysis/ice-roads-airships-could-work-together-204044251.html

¹⁵ Ibid.

¹⁶ https://www.cnbc.com/2016/07/07/giant-blimp-like-airships-are-making-a-comeback.html



Figure 9: Cost analysis of traditional ground transportation (winter roads and trucks) compared to airships.¹⁷ Each 'step' in the 'Airships' trace corresponds to the addition of a new unit to the fleet.

The advantage of being able to airlift several tons of material to remote locations is certainly appealing. To the author's knowledge, that concept has not yet materialized. It would have to be thoroughly proof tested before implementation, and would likely be used initially by the industry, given the high costs that are likely to be associated with this new northern platform.

2.2.8.2 Hovercrafts

McCartan and Kent [29] discuss an industrial design for a hovercraft meant to replace the trucks currently used to supply the diamond mine industry in the NWT (Figure 10). The rationale behind it was climate change and the challenges to come regarding such an important supply route – i.e. the sustainability of the Tibbit-to-Contwoyto winter road was considered in jeopardy. Several advantages in favor of hovercrafts were outlined [29]:

- These vehicles would operate year-long because they are capable of traveling over land, water and ice.
- For winter operation, the ice conditions, so critical for the trucks and other ground transportation vehicles with wheels, would be circumvented.
- Hovercrafts would require minimum additional infrastructure, and would be allowed to load/unload cargo with the currently existing facility (Figure 10).
- The hovercraft's cargo capacity would be up to 54 tonnes, significantly more than the average truck payload (32 tonnes for the Tibbit-to-Contwoyto operation).
- Hovercraft speed would be allowed to move at a higher speed than trucks, which has to do with their weight distribution on the ice cover.

It was estimated that, because of the cost savings for not having to build the current winter road every year, the cost of the proposed hovercraft would be recovered over a few years. Also, the year-round operation would reduce the number of hovercraft units to meet the demand for the required supplies.

¹⁷ https://www.winnipegfreepress.com/opinion/analysis/ice-roads-airships-could-work-together-204044251.html



Figure 10: Top) The type of Hovercraft Agnico Eagle would like to use for some of their activities in the NWT¹⁸. Bottom) Hovercraft concept adapted for the needs to the Tibbitt to Contwoyto winter road in the NWT [29].

Note that the hovercrafts are currently used as ice breakers elsewhere [e.g. 30], for instance, to manage ice covers in the St. Lawrence River. Evidently, that would not be the purpose of those discussed here, which would be designed not to induce ice failure.

¹⁸ http://www.cbc.ca/news/canada/north/agnico-eagle-hovercraft-gold-mine-1.4076528

3 Challenges with the winter road infrastructure

The winter road infrastructure, like any other infrastructure in Canada, faces its own challenges. Each operation is distinct – plan and usage optimization should be envisaged on a case-by-case basis. To provide the reader with a perspective of what that means, Appendix A includes the outcome of a consultation by NRC with winter road operators in Northern Ontario, who provided information on the various issues that needed to be addressed. The reader is also referred to IBI Group [6] for an instructive compilation on this topic.

In this report, we will be delimiting our attention to general trends, including those brought about by climate change.

3.1 Climate change

Climate change is the consequence of global warming, which refers to the progressive rise in temperature of the Earth's atmosphere documented over the last number of decades. At the planetary scale, this temperature rise is very small (a few degrees). But it has important repercussions on the complex dynamics of the atmosphere and can have a significant impact on local weather patterns, including an increase or decrease, depending on geographical location, of the average air temperature. A large number of climatic models have been generated in an attempt to capture these temperature trends. Figure 11 is an example – it shows a rise in temperature over most of Canada in the winter.

There is an extensive amount of literature on climate change and impact on the winter road infrastructure. Following are some recent examples:

- How it affects transportation, infrastructures and First Nations lifestyle in the Arctic [31, 32].
- How it affects winter road operations [33-36].
- How it affects the mining industry in Northern Canada [3, 22, 37, 38].
- A projection of operational lifespan in the future [28].
- The establishment of statistical links between FDD and winter roads opening dates [18].
- Historical trends and how ice bridges on the St. Lawrence can be used as an index of winter severity [39].
- Risk to communities, e.g. ability to resupply and difficulty to plan because of unpredictable seasons conditions [1].

Two factors are associated with an increase in temperature:

- *Safety concerns*: Delays in achieving target ice thickness will increase the likelihood of having users access the ice earlier than they should, because they are eager to use the ice and do not exercise due caution at that critical time of the year. This results in breakthroughs.
- *Operational aspects*: Issues that normally affect winter road operations (e.g. ground thawing, large snow falls, softening of the ice surface) on an occasional basis will recur more frequently because of climate change.

Adaptation measures and means to mitigate climate change impact will be addressed in Section 4.



Figure 11: Mean temperature increase in the winter [Source: Ouranos Consortium in 40].

3.2 Over-land segments

Over-land segments have factors and issues that need to be properly managed by the road operator. The impact of climate change is mainly related with air temperature – a reduction in FDD would delay ground freezing. In the following, we will address two aspects of over-land segments that have traditionally been an issue with winter roads, which may be exacerbated by climate change.

3.2.1 Muskeg

Muskeg, an Algonquian word meaning 'grassy bog'¹⁹, is also known as peatland. It is mostly a mixture of organic material that is either alive (e.g. moss) or decomposing in an anaerobic environment (low oxygen). Its water table – the ground water upper surface – is near the surface and is therefore exposed to freezing in the winter. Its ability to sustain a vertical load depends on its composition – to avoid failure, one needs to ensure freezing depth is sufficient for the planned loads. In places, muskeg can be affected by water circulation. Moreover, because of extensive bacterial activity, whereby anaerobic conditions promote fermentation, muskeg is a methanegenerating environment [41]. This gas is poorly soluble in water, and may contribute to the increase of ice porosity in the muskeg and a corresponding decrease in strength. Initial ice growth in muskeg is more sensitive to mild winters. Overall, the behavior of muskeg is mechanically unlike mineral soil. Winter road routing over this terrain requires careful consideration to avoid breakthroughs (Figure 12).

¹⁹ https://www.thecanadianencyclopedia.ca/en/article/muskeg/



Figure 12: A piece of machinery that went through muskeg in Northern Manitoba.²⁰

3.2.2 Permafrost

Permafrost, which is often associated with muskeg, is mostly found north of 60 deg. latitude (Figure 13), where population density is the lowest. However, it is very sensitive to disturbance and weather patterns, and is also affected by climate change [42]. Permafrost can be several hundred years old. It is divided into two layers: 1) an active layer that undergoes yearly freeze-thaw cycles; 2) a permanently frozen layer, extending several hundred meters in the colder regions, to a few meters where it is warmer. Permafrost is classified according to its distribution in terms of surface area it occupies at any given location:

- Continuous (> 80%)
- Discontinuous (30-80%)
- Sporadic (<30%)

Even where it is discontinuous or sporadic, given this terrain's sensitivity, it is a significant factor in winter road management.

Because winter roads are not used in the summer, they do not face the same engineering challenges of all-weather roads, which have to contend with a thawing active layer. In other words, the active layer below a winter road is always frozen, thereby protecting the permanent layer below. Nonetheless, in these areas, it is recommended to [7]:

- Avoid ground known to be rich in ice.
- Avoid peat deposits and muskeg.
- Plan the route so it runs over coarse grained soils, such as moraines and outwash areas.
- In areas of discontinuous permafrost, consider routing over south-facing slopes, which may be devoid of permafrost.

²⁰ http://www.cbc.ca/news/canada/manitoba/winter-road-equipment-stuck-in-manitoba-muskeg-1.984072



Figure 13: Extent of permafrost in Canada (Source: The Canadian Encyclopedia²¹).

3.3 Over-ice segments

Over-ice segments correspond to winter road C4 type (Table 1). In wooded sectors, these roads may be more exposed to the sun compared to over-land segments, since the latter may be sloping toward the north or benefit from the shade from evergreen vegetation. They may also be affected by the wind and, in places, water currents. The foundation – frozen water – is thin relative to the water column below it. A significant difference between over-land and over-ice winter road segments is related with risks of breakthroughs and their consequences. These breakthroughs are recurring events – they may or may not result in a loss of life and equipment.

The effect of a reduction in the number of freezing-degree days may be observed at locations where there is sufficient climate and winter road operational data. An example is provided in Figure 14. It shows a gradual reduction in FDDs, its consequence on ice thickness and the number of operating days in the Yellowknife area [43]. Snow data are also presented in that source (Figure 15) – the reader will recall that, because of its insulation properties, snow also has an impact on ice growth.

From a road construction and maintenance perspective, early snow removal "represents the greatest risk of a possible breakthrough" [7]. Breakthroughs happen for a number of other reasons – Figure 16 and Figure 17 are examples. Since the mechanical strength and elastic behavior of an ice cover is influenced by air temperature and solar radiation [e.g. 44, 45], higher risks are also associated with road usage late in its operational time window.

From the perspective of ice road users, some statistics have been made available [46]. This source reported a total of 442 cold water immersion deaths in Canada from 1991 to 2000, involving falls through the ice. Of those, 55% were from snowmobiling, 11% other motorized vehicles, and 34% were tied with non-motorized activities. Breakthroughs can happen even on a well-regulated winter road and professional drivers [47]. In a number of cases, the information is not available²².

²¹ https://www.thecanadianencyclopedia.ca/en/article/permafrost/

²² The author came across a case where information on a winter road operation was not released because of a casualty that had occurred on that road the previous year.



Figure 14: Temperature, ice and operational data from the Yellowknife area [43] - Top) A decreasing trend in FDD from 1943-2013. Middle) Measured ice thickness from 1959-2013. Bottom) Operating days vs FDD from 1994-2012. June 30 is considered the end of the winter at these high latitudes.



Figure 15: Snowfall accumulation in the Yellowknife area from 1943-2012 [43].



Figure 16: Breakthrough of a fuel tanker in the NWT.²³

²³ <u>http://www.cbc.ca/news/canada/north/truck-plunges-deline-ice-road-1.3477869</u>. See also, http://www.cbc.ca/news/canada/north/deline-ice-road-tanker-fuel-drained-1.3481630


Figure 17: Two other examples of ice breakthroughs from the NWT: Top) Crane lifting an excavator that went through the ice near Kam Lake in the winter of 2017-2018.²⁴ Bottom) Snow Cat near Davidson Lake.²⁵

 $^{^{24}\} http://www.cbc.ca/news/canada/north/sewage-cleanup-kam-lake-fall-through-ice-1.4506144?cmp=rss$

²⁵ http://www.cbc.ca/news/canada/north/snowcat-breaks-through-ice-yellowknife-1.4518407

4 Adaptation measures

Adaptation measures are means of dealing with issues that adversely affect the effectiveness of a winter road operation – see Golden et al. [1] for a discussion on climate change 'adaptation' concepts and how they differ from 'mitigation'²⁶. Adaptation measures can be reactive – i.e. dealt with as part of a maintenance and traffic management strategies, or they can be anticipatory – i.e. planned in advance [48]. Various sources of information discuss adaptation measures [3, 6, 15, 38, 49, 50].

4.1 Planning, construction and maintenance

Following is a non-comprehensive listing of adaptation measures – as can be seen, most apply to over-ice segments.

- Extending the power grid to remote communities, so as to reduce their reliance on diesel fuel.
- Laying structural bridges or permanent culverts at river and creek crossings when these become choke points.
- Building all-weather road segments to replace problematic areas.
- Planning route selection over the ice carefully the shortest option may not be the best, because bathymetry has to be factored in.
- Re-locating an over-ice segment to the land.
- Building and maintaining multiple routes, in case one becomes unusable, or allowing contingency room for a by-pass, as required (Figure 18).
- Conducting stress analyses to estimate ice bearing capacity under static or dynamic loads.
- Including improved standard operating procedures on ice that are embedded in contracts.
- Improving means of monitoring the ice thickness, notably by optimizing ground penetrating radar technology, temperature and strength.
- Limiting the size of windrows (snow banks on each side of the over-ice segment), which can cause a longitudinal crack to form in the center of the road.
- Periodic monitoring of the ice surface, notably to detect wet cracks²⁷.
- Maintaining a minimum width for the road so as to allow the traffic to make its way around flooded areas.
- Relying on spray ice at some locations where this method is better than surface flooding to help maintain or increase ice thickness.
- Using snow on the ice surface to maintain a high albedo that stored in snow banks can be used for that purpose, or from snow cache constructed and maintained for that purpose.
- Achieving a high albedo can also be achieved by laying out on the road surface, at vulnerable locations, a light-colored artificial material (mats).
- Preventing the accumulation of dirt.
- Covering the ice with a sufficiently thick layer of saw dust to insulate it against warm air temperatures.
- Widening road corners to improve sightlines and increase safety.

²⁶ In essence, mitigation and adaptation address the cause and the consequences, respectively, of climate change. From Golden et al. [1], "[c]limate change mitigation is the reduction, prevention, and removal of greenhouse gases from the atmosphere, whereas adaptation is planning and preparing for climate change impacts to lessen the impact or capitalize on the opportunities" (p. 411).

²⁷ 'Wet cracks' refer to cracks that allow water to seep up onto the ice surface. They indicate the crack has reached the bottom surface of the ice (it spans the full thickness), thereby affecting ice cover integrity. 'Dry cracks' are those that do not penetrate the full thickness.

4.2 Traffic management

- Using the road at night, while the ice is stronger.
- Restricting day time use of roads.
- Enforcing speed limits.
- Driver awareness campaigns.
- Allowing one lane to be faster for empty loads.
- Improving the overall traffic control.
- Proper monitoring of vehicle weight.



Figure 18: On-ice segment of the Inuvik-Tuktoyaktuk winter road in the NWT (April 18, 2012) – a by-pass was set up to go around a breakthrough [Photo by A. Barker]. Note that this road was replaced with an all-weather road, which officially opened in November 2017.

4.3 Access to ramps

The access to and from the ice cover (ramps) can be a weak link. Means of mitigating this include:

- Considering north to east facing slopes for these ramps, which are not as exposed to the sun.
- Maintaining a thick snow layer over the ramp throughout the winter, so that the bare ground does not become exposed.
- Preventing exposure of that surface to the sun by covering it with a mat or other materials.

4.4 Summary

Adaptation measures may or may not apply to a given winter operation – it is a case-by-case scenario. None are the Holy Grail. But if any single one works, it can help improve the road's effectiveness considerably. Many measures need to be implemented under the guidance of an experience operator or engineering consultants. These may be seen as a 'band-aid' approach – effective in many cases but insufficient to address the infrastructure as a whole.

5 Increasing our knowledge base

5.1 The concept of 'new knowledge'

The concept of 'knowledge' refers here to what we currently know or understand, or what we could know or understand *better*, about the winter road infrastructure. Increasing our knowledge base can lead to innovation and new ways of doing things. This concept contrasts with adaptation measures such as many of those listed in the previous section, which were learnt from extensive field experience. New knowledge can apply to all three elements shown in Figure 1, but as mentioned before, in this report we focus on that related with science and engineering.

5.2 The concept of 'R&D'

Acquisition of new knowledge is usually tackled through R&D, a process involving targeted investigations using standardized procedures, and meant to provide answers the specific questions on which information is lacking. They are typically conducted by research institutions and universities, and to some extent also by the industrial sector (although in that case the outcome may be proprietary, i.e. other stakeholders cannot make use of it). R&D can be based on theory, numerical modeling, laboratory experiments, field tests, analyses of full-scale data, or any combination thereof. Its ultimate outcome is new information, which may then feed into guidelines, standards and working practices.

R&D requires time before it bears fruit – several years, depending on its nature. The outcome as planned initially may change in the course of the investigations. That is one of the consequences of dealing with unexplored territory. Overall, R&D is considered an investment, meant to pay off in the medium to long term.

5.3 Prospective R&D to improve winter road safety and effectiveness

In this section, knowledge gaps are identified – these are topics that, from NRC's perspective, are considered good candidates for R&D. They are divided into two avenues of investigations:

- 1. Road characterization and usage.
- 2. Addressing the integrity of floating ice segments.

Table 3 provides a first-order description of these two avenues.

5.3.1 Road characterization and usage

Winter road characterization is the information that one can obtain from a road both over-land and over-ice, in order to know what it is, what it is made of, how trafficable it is, opening and closure dates, the number and types of vehicles, the nature of the goods being hauled, etc. The novelty with this tool lies in its ability to collect information on the roads' physical parameters listed in section 2.2.4, which can then be combined with all operational and logistical data (e.g. opening and closure dates, nature of goods transported) in an interactive database.

5.3.1.1 Gathering the information

A means of systematically quantifying various key physical parameters would be a valuable tool for winter road characterization. For instance, a ground penetrating radar (GPR) is commonly used to obtain a continuous thickness profile of the frozen ground [51, 52] and freshwater ice [19, 53, 54]. The package would enclose additional instrumentation, which would increase its capabilities significantly, notably a compass, tilt meters, accelerometers, proximity sensors, cameras, GPS, voice data logger, amongst others. A full 3D representation of routing could be

obtained, with grades, cross-slopes, angles of turn, road width, orientation of slopes on over-land segments, location of ice crossings, ice and snow thickness, etc.

	Road characterization and trafficability	Addressing the integrity of floating ice segments
<i>Objectives</i>	To design a tool for the systematic collection of physical parameters and usage information of winter road operations, and to share that information with stakeholders.	To look into several outstanding questions regarding the bearing capacity and deformational behavior of floating ice roads.
Rationale	Availing this information would benefit the road users and populating a database would be used for traffic analytics purposes.	Answers to the questions addressed would feed into guidelines and design codes about winter/ice roads.
<i>Time frame for applicability/readiness</i>	2 to 4 years	3 to 6 years
Likelihood of support from provinces/territories ^(*)	Medium to high	Low to medium

Table 3:	Investigation	avenues	proposed	l in	this	report.
I abic c.	in , congation	avenues	proposed	* ***	UIIIG	1 CPOI G

(*) This estimate is based on previous stakeholder communication – provinces and territories have priorities and are mostly concerned with immediate to short-term outcome.

Real-time access via satellite linking could provide short-term information, accessible to users on a weekly or even daily basis. Yearly databases would be available for extensive analyses by stakeholders. This may be technically challenging and would also need to be investigated.



Figure 19: Left) The SmartQAMUTIK with its on-board ice thickness-measuring device.²⁸ Upper right) A GPR on a sleigh behind a vehicle [from 38]. Lower right) Example of a GPR output [from 55].

Interestingly, as explained on the SmartICE website, "[a] 2010 survey of residents in Nain (Nunatsiavut), following an extremely warm winter, indicated that 75% of sea-ice users could no longer predict ice conditions. It also found that 1 out of every 12 people surveyed had fallen through the ice the previous winter."²⁹ While this may or may not apply to in-land winter roads, a similar impact for these roads is conceivable. The implication of the local communities, in the case of community-run operations, would promote increased collaboration, education and self-reliance. It would be an opportunity to integrate traditional indigenous knowledge to further improve our understanding of ice covers [1]. It could also be a means for the communities to reaffirm the ownership of their road network and foster an interest for a more systematic and consistent documentation of the roads. There is thus a clear advantage in incorporating a social component into a road characterization scheme.

Way forward

As indicated elsewhere [6, p. 35], ground-penetrating radar would promote the "frequency and accuracy of measuring ice thickness, with benefits for both road construction and maintenance phases, while also better preserving the integrity of the road system compared to ice boring methods." An instrumented package for usage on winter roads is a promising avenue. We would have to see to what extent winter road stakeholder needs could be best addressed by that system. A careful assessment of that tool and of its feasibility would be required.

²⁸ http://www.cbc.ca/news/canada/north/smart-ice-pond-inlet-nunavut-1.3764542

²⁹ https://www.smartice.org/

5.3.1.2 Combining with operational data

In parallel, operational data for each road – opening/closure dates, number and type of vehicles, number of people traveling, nature and amount of goods (fuel, construction supplies, food supplies) – would be gathered and combined with the information collected by the road characterization system.

Way forward

The operational data would be gathered by engaging and coordinating with collaborators at the federal level (e.g. Transport Canada, ISC, CIRNA).

5.3.1.3 Sharing the information

A web site could be designed to allow stakeholders (operators, users, analysts in transportation logistics) access to the road characterization data. Such a tool would either apply specifically to the winter road infrastructure, i.e. designed from scratch, or it could be an extension to an existing one – either option would have to be looked into. It would enclose information on parameters such as those listed in section 2.2.4 with all available information on road usage and transportation logistics. This would be a two-step procedure:

- 1. Tool design/adaptation.
- 2. A plan for on-going year-to-year maintenance.

Community involvement in the deployment of the data gathering tool could help ensure data acquisition is done on a regular basis. It could also facilitate on-going communication between communities and the governmental organizations. For instance, in Northern Ontario, the operations are funded on a per-kilometre basis. However, "[c]ommunities that have more difficult water crossings or other challenges along their route are compensated the same way as those with fewer challenges"[6, p. 27]. Proper road characterization would alleviate this kind of situations.

Overall, the outcome would be a database that decision makers could use to better visualize transportation of goods and people, as well as for the purpose of multimodal transportation planning. Ultimately, one might envisage availing road users with day-to-day information on road conditions, or perhaps, week-to-week.

Way forward

Provided the deployment of this field tool is deemed feasible, the following step would be to see what currently exists in terms of transportation database and web-based interfaces. Network access may be limited in northern locations – that would have to be addressed also. Such a resource was flagged as a need for Ontario winter road stakeholders. For instance, IBI Group [6, p. 35] calls for technological advancements, notably "[0]nline applications for information-sharing about winter road conditions, such as the one showing the condition of Northwest Territories highways and winter roads [...], which are increasingly easy to implement."

5.3.2 Addressing the integrity of the floating ice segments

This approach would consider several outstanding questions regarding the bearing capacity and deformational behavior of floating ice roads. Answers to these questions would contribute to a safer usage of over-ice segments and would feed into guidelines and design codes about winter/ice roads. These questions are discussed below (see Appendix E for a summary).

5.3.2.1 Bearing capacity – How much load can floating ice sustain

Ice bearing capacity, the ability of a floating ice cover to sustain a given load, has typically been determined using what is traditionally known as the 'Gold' formula, from Lorne Gold, former

NRC scientist (Appendix B). This formula is universally used by engineering consultants as a first approximation to estimate loads, with various values for the 'A' parameter [e.g. 38]. If required, it can be supplemented by a more elaborate stress analyses for critical cases, such as for an inordinately heavy vehicle. For local communities, charts based on that formula are the best option (Table 4) because of their simplicity, which is why they are commonly found in winter road guidelines.

Table 4: Example of a load table from an Ontario guidelines [56]. Note guidance toward a
proper value for the 'A' coefficient.

	Low Risk	Allowable L	.oad (P=kg)	Substantial Risk	
h=Effective Ice	A=3.5	A=4	A=5	A=6	
Thickness (cm)	Low Risk (kg)	Tolerable Risk (kg)	Moderate Risk (kg)	Substantial Risk (kg	
20	1,400	•		•	
25	2,200		*	*	
30	3,150	•	•	•	
35	4,300	4,900	6,120	7,35	
40	5,600	6,400	8,000	9,60	
45	7,100	8,100	10,100	12,10	
50	8,750	10,000	12,500	15,000	
55	10,600	12,100	15,100	18,10	
60	12,600	14,400	18,000	21,60	
65	14,800	16,900	21,100	25,30	
70	17,100	19,600	24,500	29,40	
75	19,700	22,500	28,100	33,70	
80	22,400	25,600	32,000	38,40	
85	25,300	28,900	36,100	43,30	
90	28,300	32,400	40,500	48,60	
95	31,600	36,100	45,100	54,10	
100	35,000	40,000	50,000	60,00	
105	38,600	44,100	55,100	63,50	
110	42,300	48,400	60,500		
115	46,300	52,900	63,500		
120	50,400	57,600	**	**	
125	54,700	62,500			
127	56,450	63,500	**		

There is a tendency for these guidelines to be conservative, i.e. to underestimate the amount of load an ice cover can sustain, for various reasons. One is the consequence of a breakthrough. As Proskin et al. [7] point out, "[the] negative publicity and the reputation for risk of floating ice often makes planners slow to increase loading in their transportation planning." Another reason is the complexity of the ice in nature, and our limited understanding of it. That extra leeway is to cover for the large number of contingencies, inherent to an infrastructure that is not as well-documented, well-regulated and well-controlled as other surface transportation systems in terms of construction, maintenance and usage.



Figure 20: A block of ice showing clear ice (bottom of the ice block) and white ice (top of the ice block), the latter with internal layering.

In general, for simplicity sake, an ice cover is viewed as a uniform material of a given thickness, strength properties and elastic behavior. However, in most cases, it is a multi-layered non-uniform material (Figure 20). The layering is mostly due to the existence of clear ice (also called blue or black ice) and, particularly, white ice. The latter results from water soaking of the snow cover that naturally accumulates on top of floating ice expanses [57, 58]. It can also form as a result of maintenance-related surface flooding, typically used to artificially thicken the ice surface or to repair it.

There is currently a lack of agreement as to how to incorporate the thickness of white ice into the Gold formula [14]. Depending on which guidelines one is reading or which operator one is speaking to, the white ice is either left out altogether, it is included, or it is included only if it results from artificial flooding (otherwise it is omitted). There is also a lack of agreement between various sources of information about the value assigned to the 'A' parameter in Gold's formula. All in all, depending on what source of information one might rely on, a different bearing capacity will be prescribed (Figure 21).

Way forward

A better understanding of how an ice cover reacts to a vertical load can be achieved by combining experimental trials in a large test basin with an instrumented ice sheet of known thickness and layering. Deflection would be recorded under load, and the output of these experiments used to calibrate a numerical model – NRC has already conducted preliminary feasibility studies on the numerical approach [59, 60]. This would be done by varying the nature of the ice sheet and the applied load. Breakthrough conditions could also be investigated.



Figure 21: Recommendations from 14 sources, assuming a total ice thickness of 40 cm made of clear ice and natural white ice in equal proportion and of questionable quality [14]. Note the lack of agreement.

Testing at a larger scale could be done, such as those of Laidley et al. [61]. Ultimately, deflection could be measured in a real case scenario, on a real ice road. The final outcome would be more reliable recommendations for the 'A' coefficient and how that coefficient might be affected by layering.

5.3.2.2 Static loading – How long can a load remain stationary on the ice

Gold's formula is not meant to be used for loads that remain at one location for a certain time period. The reason is that, after a certain amount of time, failure of an ice cover that safely supports a non-static load could occur. That is because, with time, the stresses induce non-elastic deformation in the form of micro-cracks [e.g. 62], which develop into large cracks and, ultimately, breakthrough [e.g. 63](Appendix C).

In general, the heavier the load, the less time it should be allowed to remain on the ice. As to what the length of that time period is, different guidelines have different recommendations. Some, for instance, specify that Gold's formula should only be used for moving loads [12, 64]. Others specify a two hour limit [56, 65], which is also what Gold [66, p. 179] prescribed.

If a load has to remain on the ice, some guidelines advise to monitor the freeboard by drilling a hole through the ice. When the water level reaches the ice surface (i.e. the freeboard reduces to zero), the load has to be removed (N.K. Sinha, pers. comm. 2018). This practice is supported by the analyses of Frederking and Gold [67] and has been validated by many sources [e.g. 56, 65, 68]. BMT Fleet Technology [69] recommends to use a time-dependent reduction factor if the load duration is to exceed 15 minutes – the longer the duration, the lower the allowable load. Proskin et al. [7] mention that "if the freeboard is found to be less than 0.04 times the ice thickness, then the ice should be unloaded, repaired or the area closed."

The foregoing demonstrates again a lack of agreement in the recommendations which, as before, stems from an incomplete understanding of how the ice deforms.



Figure 22: Several vehicles parked on the ice for fishing activities.³⁰

Way forward

In the evaluation of its mechanical response, ice has historically been treated as a perfectly elastic material. That is to say, its response to a load is immediate and the resulting deformation is entirely recoverable upon load removal. In reality, that is not the case. In Appendix C, the mechanisms are described and the theory is summarized. It also explains the difference between the Young's modulus, a material property, and the 'effective' modulus, an artefact that is being used in many analytical treatments.

It would be helpful to implement these concepts into a numerical model, because that would allow a better understanding of ice behavior under a static load. This could be done in parallel with the experimental work described previously, and implemented in the field on a fully instrumented ice cover. Acoustic sensing technology could be used, which would document cracking activity in the ice cover [70-72]. The relevance of this work can be seen in the context of vehicles parked on the ice while ice fishing (Figure 22), or when estimating the risks of vehicle being forced to stop on the ice, due to a breakdown, a snow storm or any other motive.

5.3.2.3 Dynamic loading – How fast is too fast

From the two previous sections, we have seen that an adequate ice bearing capacity has to take into account the nature and thickness of the ice (5.3.2.1) as well as the time of load application (5.3.2.2). A third factor is vehicle speed. Near a certain speed, referred to as the 'critical' speed, a wave pattern is generated ahead and behind the vehicle, which amplifies the deflection [7, 38, 73-75](Figure 23). Parameters promoting this phenomenon, in addition to speed, are ice thickness, vehicle weight and water depth.

³⁰

https://www.google.ca/search?q=ice+fishing&rlz=1C1CHBF_enCA713CA714&source=lnms&tbm=isch& sa=X&ved=0ahUKEwiTuISG0drZAhWjct8KHeAZC_EQ_AUICigB&biw=1527&bih=872#imgrc=JQQ5I XenkX37_M:



Figure 23: Schematic representation of a large vehicle traveling on a floating ice cover. Top) Wave pattern *below* critical speed. Bottom) Wave pattern *above* critical speed. Modified after Mesher et al. [19].

A recent study by van der Sanden and Short [76] documented rather remarkably this wave pattern from satellite observations [76](Figure 24, Appendix D). The images were from Gordon Lake along the Tibbitt to Contwoyto Winter Road in the NWT. Several patterns were captured, confirmed by a theoretical analysis [77]. They allow one to clearly visualize the effect of a moving load. This was a unique instance – wave patterns in an ice cover had never been documented so convincingly.



Figure 24: Top) The TanDEM-X satellites that detected wave patterns in the ice.³¹ Bottom) The wave pattern ahead and behind a vehicle (red dot) moving in the direction of the yellow arrow. The black lines are the output of the theoretical modeling [77].

Risks of dynamic loading are higher on ice roads used by large vehicles. Even with lighter vehicles, speed limits have to be prescribed. Proper signage and drive awareness are key mitigation measures. Another one is dividing the traffic in two classes on the basis of weight, with the unloaded trucks allowed to go faster (using an 'Express lane') than the loaded trucks [7].

Spacing between vehicles is also important – if it is too short, this will also promote risks of failure, which occurs as a result of excessive ice cover deflection due to these waves. For instance, on the industrial Tibbitt to Contwoyto Winter Road operation, a minimum distance of 500 meters is prescribed. More specifically, as recommended by Proskin et al. [7, p. 53], "[f]or

³¹ https://directory.eoportal.org/web/eoportal/satellite-missions/t/tandem-x

light vehicles (less than 5000 kg) the following distance between vehicles should be at least 200 times the thickness of the ice. For heavier vehicles (5000 to 40,000 kg) the following distance should be increased to 500 times the ice thickness. If the water body is smaller than these limits, then only one vehicle should be permitted on the ice cover at a time". Other safety measures are to try to plan on routing above deeper waters, and to see that the road meets the shoreline at an angle, e.g. 45 degrees, as opposed to perpendicular to it. The reasoning behind these latter measures is that deflection is higher where the water is shallowest. Approaching the shoreline perpendicular to it means the wave will be directed straight at it, promoting the chances of ice failure ahead of the vehicle.

This phenomenon – the production of waves ahead and behind a moving vehicle – is still being debated [74, 75]. A number of recent field studies have been done to fill in some of the knowledge gaps. Moreover, according to the theoretical work conducted on the satellite images [77], it appears that the prescribed distance between the vehicles may be substantially overestimated, and the critical speed underestimated. If this is confirmed in future studies, vehicle speed would have to be reduced and the distance between each could be reduced.

Way forward

Studies on dynamic loading need to be sorted out. Here again, physical testing, as required, either in the laboratory or from an operational ice road, or both, would assist in gaining additional insights into what happens to an over-ice segment under dynamic loading. Instrumentation output would serve to validate numerical models. The work described in [71] would be a good starting point.

5.3.2.4 Cracks patterns – Do they weaken the ice?

Natural ice covers are always fractured – airline fissures can be readily seen, provided the ice happens to be transparent (Figure 25). These fissures are typically the outcome of air temperature changes, leading to contraction and expansion. They can also be a result of repetitive loading due to vehicle traffic (Figure 26).



Figure 25: Crack network inside an ice cover (boot for scale). The crack surfaces are generally vertical, albeit with various orientations.





Figure 26: Two sources of cracking. Top) An overnight decrease in air temperature, for instance from -5°C to -20°C as shown here, will induce a tensional regime in the upper part of the ice cover, and result in cracking. Bottom) Repetitive loading from vehicles, here as part of field testing (instrumentation in the orange huts) [74], will also induce cracking.

Fractures may be seen as structural flaws, but their influence on the integrity of a floating ice cover has never been investigated so far, to the author's knowledge. As stated by Proskin et al. [7], "[a]ny of the refined analytical methods [to determine bearing capacity] assume the ice sheet acts as an elastic, homogeneous, isotropic plate on an elastic foundation. This assumption is sufficiently accurate for the purpose of designing ice roads, despite the fact that cracks are normally present within ice cover" (p. 64). In other words, these types of flaws are typically overlooked.

The Tibbitt to Contwoyto Winter Road management pointed out the uncertainty tied with loadinduced cracks in the ice [20, p. 13]. Concerns about cracks were also raised by a manager of the Regional municipality of Wood Buffalo, in Alberta (I. Haq, pers. comm. 2015). Moreover, a 2016 breakthrough of a tanker in the Deline area, NWT, was linked with a crack in the ice³² (Figure 16) but no other details about it were available as of this writing. Also, a factor that could have contributed to the Deline breakthrough was said to be the weight of the vehicle, which was 10% over the allowed weight limit of 40,000 kilograms. However, given that such limits are usually conservative, one may question if this factor had anything to do with the breakthrough, i.e. it may conceivably have occurred had the truck's weight been below that limit. On the other hand, the nature of the cracks in the ice cover varies, and the cumulative effects are unpredictable.

Way forward

There are a number of ways this topic could be investigated. One is to monitor the development of a crack network over time at a target location, both away and near an operational ice road. Mechanical testing of ice blocks, in the laboratory, with various crack densities (e.g. none, low, high) could be conducted. Cyclic loading of a similar nature as done before [78, 79], specifically designed to address the ice road context, could also be considered. These studies would yield valuable information on to what extent cracking affects ice bearing capacity.

5.3.2.5 Means of reinforcing an ice cover

At the road routing stage, it is not always possible to avoid areas known to be vulnerable, e.g. ice exposed to erosion from below by a nearby stream, shoals or just a creek crossing, a perpendicular approach to a shoreline, a river crossing that needs to be accessed early in the winter. In these circumstances, means of reinforcing the road are required. This can be done (and has been done over the last number of decades) in a number of ways. In the context of a warming climate, especially with the support of R&D, this approach is expected to become increasingly instrumental in preserving the yearly operational lifespan of winter roads.

Ice cover reinforcement can be divided into two types: macroscopic and microscopic [80].³³

- Macroscopic reinforcement includes the recourse to wooden logs [66, 81, 82](
- Figure 27), cables [83, 84], geo-fabrics [85-87] and steel bars [88].
- For microscopic reinforcement, the ice itself can be produced by mixing water with another material (e.g. wood pulp, fiberglass) before freezing [89-94]. Specimens produced from these mixtures are usually tested in the laboratory to assess their strength. An example of such a test is shown in
- Figure 27.

Ice reinforcement involves a number of factors:

- Material availability the economic aspects of it are discussed elsewhere [80, 91, 95].
- Extra time needed to build the road [82, 83].
- Darker materials absorb solar radiations and contribute to ice deterioration [83, 86].
- Depending on the reinforcing material, it may have to be recovered for environmental reasons, which may prove unfeasible [85].
- Material deployment in the field depends on its nature it may be difficult to position and freeze in the ice cover [86].

³² http://www.cbc.ca/news/canada/north/deline-ice-road-crash-infrastructure-report-1.4545787?cmp=rss</sup>

³³ By analogy, this is like using re-bars and microfibers, respectively, to reinforce concrete. Note that both concrete and ice react in a brittle fashion when loaded in tension.







Figure 27: Top) Example of an ice cover reinforcement with wooden logs [81]. Middle) The red dotted line is a geomembrane able to sustain additional load. Bottom) Example of beam bending test set-up used to measure ice strength [96].

Way forward

The next step in moving forward with the investigation of strengthening methods would be to get a detailed account of what these methods are. The purpose would be to know if the material has actually been applied on a winter road operation, under what circumstances, and what information on performance and limitations could have been gathered. For instance, deployment and retrieval may be problematic. This background work would be used as a stepping stone toward what could be deemed promising avenues, i.e. starting materials, that would be tested in the laboratory, then in the field.

6 Discussion and recommendations

Former Manitoba Infrastructure and Transportation Minister, Steve Ashton, was quoted as saying on winter roads: "They are dollar for dollar one of the most cost-effective transportation initiatives you can bring into place."³⁴ They clearly are an important component of the surface transportation network in the North, and are becoming more so with an increase in northern developments. These roads are sensitive to climate change.

Winter roads in Canada are under provincial or territorial jurisdictions – in some of these jurisdictions (e.g. Ontario, Quebec), road management is delegated to local communities. The industrial sector is active throughout the country. These stakeholders approach their winter roads in their own way, in response to their own needs and socio-economic requirements. Guidelines exist, but are different across the country, and they are not compulsory. Understandably, therefore, there is no uniformity at the national scale. In this report, we took a step back and tried to capture the general picture and identify common denominators. The characteristics, effectiveness and safety of the Canadian winter road infrastructure were overviewed, mostly from a scientific and engineering perspective. On that basis, winter roads cannot be divided according to political (provincial, territorial, regional) or cartographic boundaries (e.g. above or below 60 deg. latitude) – they must be looked at globally. Extending our inquiries beyond international boundaries (NRC communicated with stakeholders from Alaska and Russia) for additional input should also prove beneficial, so as to see and compare approaches used in other countries.

Based on the findings presented herein, as well as on NRC's experience in studying the Canadian winter road infrastructure over the last number of years, following are three recommendations to be considered as a way forward.

6.1 Documenting the Canadian winter road infrastructure

It is here suggested that winter roads and climate adaptation measures be addressed at the federal level. The entire infrastructure could be assessed holistically, by integrating all factors, such as full winter road characterization, usage forecast and capacity, its role in multimodal transportation and means of centralizing/accessing all information. Most importantly, a coordinated effort would incorporate all relevant socio-economic element, as well as environmental and climatic parameters. To do so, a 'road map' would be helpful so as to better coordinate efforts by the relevant federal organizations – e.g. Indigenous and Northern Affairs Canada, Transport Canada, Environment and Climate Change Canada, Natural Resources Canada, National Research Council of Canada. This initiative would require careful coordination.

The various outputs and outcomes from the federal endeavor could benefit other jurisdictions, for instance in assisting their decision makers with prospective road re-alignments, and prioritize full, partial or incremental replacement of winter road with all season roads. This would help achieve the right balance between 1) benefits of providing year-round over-land access to remote communities and 2) the implementation costs and environmental and social impacts of these roads [e.g. 6].

The outcome of the proposed R&D investigation avenue on road characterization (section 5.3.1) would be one of the building blocks of that initiative. The system described in this report could be adapted and implemented country-wide, with the following prospective benefits:

³⁴ https://www.winnipegfreepress.com/opinion/analysis/ice-roads-airships-could-work-together-204044251.html

- Uniformity in data collection across provincial/territorial boundaries.
- Assistance to all operators in road planning, maintenance and usage.
- Increased community involvement.
- Synergy between scientific/engineering expertise and First Nation's traditional knowledge base [1].
- Data for capacity and multimodal planning, and to guide priorities on road realignment and incremental replacement (partial or complete) by all-weather road segments.

6.2 Filling in outstanding knowledge gaps in ice bearing capacity

Over the last few decades, there has been a clear disconnection between academia on the one hand, and the reality of winter road operations on the other. Conceivable reasons for this state of affairs include the following:

- Stakeholders from R&D organizations investigating cold regions phenomena typically publish their results in the scientific and engineering literature, which is not palatable to stakeholders outside academia.
- R&D results are also presented at conferences, with relatively limited specialist/non-specialist interaction at these meetings.
- Winter roads have historically occupied a relatively small portion of yearly budgets in transportation departments, with relatively (and understandably, based on the two previous bullets) little incentive to integrate new R&D in guidelines.
- R&D is expensive. The limited amount of available funding currently available is channeled instead toward more immediate operational requirements, i.e. to ensure winter road remain safe and effective on a day-to-day basis.

There are three consequences:

- 1. Our current scientific/engineering knowledge base is not being capitalized on. For instance, our understanding of the physics and deformational mechanics of ice has evolved considerably since the 1970's but it is not being fully applied to guide design.
- 2. Important knowledge gaps, such as those discussed in this paper, are being overlooked.
- 3. Long-term provisions for climate change effects are not being addressed.

The knowledge gaps outline herein (section 5.3.2) could be addressed, supported by a numerical modeling tool made available to stakeholders. Further down the road, discussions could be held between stakeholders, to examine the relevance of a user-friendly app for ice road usage and maintenance, adapted to their needs.

6.3 Moving toward guidelines consistency

As it stands, there are several guidelines in the country, published under the various provincial and territorial jurisdictions, varying in years, and inconsistent in a number of ways. Moreover, as pointed out by Proskin et al. [7, p. 17], "[e]xisting literature does not have consistent terminology for describing winter roads because differing classification systems were developed with varying perspectives and for project-specific applications. Provincial and territorial guiding documents often use descriptors and terms in different ways to add to the confusion". Consistency is lacking even within a jurisdiction.

Some alignment has occurred over the recent years, namely between the guidelines promoted by the Transportation Association of Canada [7], the Government of Alberta [9], Ontario's [56] and the NWT's [11]. That trend is encouraging.

Consideration could be given to a full re-alignment of the existing guidelines, to make them more comprehensive, and updated with the currently existing knowledge base generated by all R&D organizations. This could be conducted under the umbrella of a committee supported, for instance, by a federal organization or a standards association.

7 Conclusion

Climate change affects the effectiveness and safety of the Canadian winter road infrastructure. A reduction in the number of freezing-degree days, which decreasdx its yearly operational lifespan, is the most recognized concern. Over-ice segments take longer to freeze to the required safe thickness, thereby delaying road opening. Users may get onto the ice too early in the season, when the ice has not yet achieved a safe thickness. Road closure at the end of the season may come earlier than expected, or occur mid-season during warm spells. One main contributing factor in road closure is a softening of the ice surface (typically in the afternoon), which is then no longer trafficable. Poor road rule enforcement and lack of information contribute to the risks.

The safety and effectiveness of winter roads are not only about the road itself and impact of climate change, but also how it is used and maintained. This is not uniform across the country – it varies according to who the operator is (government, local communities, industrial sector), the location or geography and the nature of the traffic.

This report outlines several investigation avenues that could be explored through research and development (R&D) – all would work toward increasing the winter roads' safety and effectiveness. They are divided into two avenues: 1) A fully instrumented tool for road characterization and trafficability, and 2) addressing the integrity of floating ice segments. The *first R&D avenue* is about data gathering and sharing. The prospective tool and associated database would have the shortest return on investment time, depending on the availability of currently existing database interfaces. It could also be of interest to provincial and territorial authorities, as well as to local communities, because it would facilitate data gathering, promote communication, and increase user and operator awareness of their operations. This could be used for capacity and multimodal planning, and to guide priorities on road realignment and incremental replacement (partial or complete) by all-weather road segments. The *second R&D avenue* directly addresses knowledge gaps in the mechanical behavior of ice covers under loads. The outcome would feed into updated guidelines and codes of practice on winter road planning, usage and maintenance, and would increase coherence between these documents across Canada.

Drawing on these considerations, three recommendations are made: 1) The implementation of a system to gather data on road description and usage; 2) addressing the knowledge gaps outlined in this report; and 3) working toward nationally-consistent, more comprehensive winter road guidelines, incorporating new knowledge base.

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APPENDIX A – CONSULTATION OUTCOME

with Northern Ontario winter road operators

In October and November of 2015, NRC communicated by telephone with representatives from Northern Ontario winter road operations. These conversations were informal and meant to get information on their road, for instance, length, over-land vs over-ice, who the users are, what issues they were facing, what caused them to close the road, and what guidelines they used. Answers to these questions were not always obtained, to some extent because the representative did not know or chose not to answer.

For the sake of privacy, the details of these conversations will only be summarized here, without names or provenance.

Operations

- Asheweig
- Bearskin Lake
- Cat Lake
- Deer Lake
- Eabametoong
- Fort Severn
- Kasabonika Lake
- Keewaywin
- Kimesskanemenow Corporation
- Kingfisher Lake
- Kitchenuhmaykoosib Inninuwug
- Koocheching
- Marten Falls
- Moose Cree
- Moosonee (Town of)
- Muskrat Dam
- Neskantaga
- Nibinamik
- North Caribou Lake
- North Spirit Lake
- Northwest Angle #37
- Pikangikum
- Poplar Hill
- Sachigo Lake
- Sandy Lake
- Temagami
- Wapekeka
- Wawakapewin
- Webequie
- Weenusk

Issues with their roads

Listed below are some of the issues that were brought up during these conversations. These items are in no particular order – the reader, it is hoped, will get a feel for the general outcome of these conversations.

- Climate warming causes early thaw in the spring.
- Warm spells are a recurring mid-season issue.
- Users include hydro companies and Ministry of Transportation.
- The seasons are getting shorter.
- Road users include commercial suppliers (semi-trailers), but the number of vehicles is not monitored.
- 'Accidents' are rare mostly 'incidents'.
- They do their own construction and maintenance with their machinery.
- One structural bridge³⁵ is used by heavy equipment, even though it was not designed for it.
- There has been significant road damage during installation of a fiber optic cable, in the middle of the road.
- A 15-km section is in a swamp and takes time to freeze two machines bogged down the previous season. Re-routing would be required but that requires funding.
- The seasons are getting shorter overnight driving is recommended, but the roads are not controlled.
- There are many incidents, related with driving too fast and drinking/driving the road is not patrolled by the police.
- An over-land section exposed to sun rays is the weak link forcing road closure.
- The road is long, which causes safety issues.
- The road is underfunded.
- Snow drift is hard to manage for such a long road people get stuck every winter which has been reported to the Government of Ontario.
- Hilly terrain, tight turns, narrow roads cause problems.
- Warmer weather over the years causes a 59% reduction in road usage.
- Underfunding.
- Shortening of yearly operational lifespan seasons (soft surface, creek melting).
- Conflicts with trappers, who want compensation for disturbance of their activities.
- An ice ridge formation on a lake (probably due to thermal expansion) would require new routing.
- Road closure is mostly based on trafficability, when small cars are not able to use it due to a soft ice surface, although four wheel drive vehicles still use it.
- Large windrows on over-ice segments are difficult to remove and cause the ice to sink.
- Drinking and driving is the main safety concern.
- Boulders are in the way in the portages, and would need gravel to keep vehicles from sinking in.
- Mild climate means more surface flooding (with pumps) is required.
- No control over access people go over the road when it is too soft, inflicting damage on it.
- Meetings with MNDM and with INAC no longer happen why?
- Last year, a wet crack developed alongside the road, making it unsafe (or perceived to be such by the trucking company), so they had supplies flown in.
- A proper ice thickness is important if a diesel truck makes it through the ice, it will spoil their drinking water.

³⁵ This is a bridge made from wood and steel.

- Road widening would be desirable.
- Warm weather is shortening the operational lifespan (although the previous season's duration was good three months).
- Re-alignment would be required to fix tight turns, which they reported to MNDM (but MNDM would like to see evidence of them, e.g. air photos).
- Contamination of water by vehicles (oil, coolant) is a concern.
- Structural bridge would be good.
- Insufficient equipment grader not strong enough and in poor shape.
- Fisherman makes holes too close to the road, which causes flooding.
- Increase in number of trucks over the years with an increase in mining activity.
- High fuel cost and increase in traffic would justify a major upgrade (not done since early 1990's) for safety purposes.
- Warming climate is forcing them to operate with thinner ice road (the trucks are half-loaded but they still pay the full price).
- Vehicle weighing not always nearby.
- Issue with a 'ramp' next to the town as it stands, the traffic causes damage to water main.
- Better equipment would be required.
- Climate change shortens the season and reduces the ice thickness.
- The funding they get (\$500k) is not sufficient.
- A structural bridge over three creeks would be more practical than cutting and laying lumber over it every year.

Guidelines used by the winter road operators

Little information was provided to NRC regarding the guidelines used to help with building, usage and maintenance of their road. Truck companies appear to have their own. One operator used the one from de Beers, available on-line. In a number of cases, the representative said he/she did not know which one, or if any were used. There were also the occasional allusions to the 'provincial guidelines'.

APPENDIX B – GOLD'S FORMULA

Gold's formula

In the 1950s, Lorne Gold, a scientist with the National Research Council in Ottawa, was looking for a way to help ice road users determine how much weight an ice cover of a given thickness could safely sustain. Analytical methods already existed at the time (and are still being used by engineers and scientists). However, they were relatively complex and thus not practical for ice road users who did not have the technical background to understand them. These methods also made assumptions (*e.g.* uniform ice, no cracking) that were not representative of real ice.

Gold collected information from the Pulp and Paper industry on breakthroughs that had occurred, including data on ice thickness and weight, of the vehicles and horses that caused the ice to fail [66, 97]. From this information, he borrowed a formula from Russian researchers [see short summary in 98] and used it in conjunction with the breakthrough data to come up with a method that, to this day, is used as a guideline for ice roads, platforms and landing strips. This formula has the following form

$$P = Ah^2$$

Where

P: Design load *A*: Empirical parameter with pressure units *h*: Ice thickness

The parameter A is related with the ice flexural stress. As discussed later, the value assigned to it varies widely. The thickness h is assumed to be representative of the ice road as a whole (or a section thereof) with due consideration to prospective variations.

With this formula, a plot can be produced, as shown in the figure below, that can be used as guidance to determining what a safe load could be for a given ice thickness. The 'A' values used by Gold in this plot are 3.5, 18 and 70 kg/cm², retained for the following reasons:

- The first one was the lower bound value for reported breakthroughs, i.e. none (or few) occurred below this line.
- The second value is the upper bound value for successful use of ice covers, all of which plot below that line.
- The third value is for a line above which no breakthroughs were observed.

Eq. 1



Load as a function of ice thickness for the three different A values used by [66].

Although simplified, these considerations capture some of the fundamentals of ice road design. Guidelines are typically conservative, i.e. the ice cover could support loads higher than the maximum allowable. Masterson [68], for instance, alludes to 500-550 kPa as a typical allowable stress for a flexural strength of 1.5 MPa, which a corresponding safety factor of 3.0.

It should be borne in mind that Gold's formulation is based on 'empirical' evidence: it relies on observations of real events, not solely on theoretical concepts. It is a curve-fitting exercise -a best-fit line describes the relationship between two parameters, namely ice thickness and loads. This line may be seen as an 'envelope'. Above it, the probability of a breakthrough caused by a number of factors (localized thin ice, presence of a crack, high vehicle speed, etc.) is deemed unacceptable by the guidelines.

APPENDIX C – ICE DEFORMATION

The theoretical treatment below has been elaborated by N. Sinha, formerly from NRC. It describes basic mechanisms that take place in ice under deformation. This theory has yet to be incorporated into a numerical model to assess ice cover response to vertical loading.

Components of deformation

Let us consider what happens to an ice specimen submitted to a constant load, and is unloaded at some point during the test (left-hand figure below). The deformational behavior, as indicated in that plot, points to three distinct components: elastic (E), delayed elastic (D) and viscous (V). The elastic component E is instantaneously recoverable upon unloading. The delayed elastic (or anelastic) component (D) is also recoverable but requires time. The viscous (or plastic) component (V) is permanent. In the right-hand figure below, each of these three components is plotted on its own, which helps visualize the effect of different deformation mechanisms.

The elastic component

If we assume no micro-cracking takes place, the elastic component remains stable throughout the loading phase. This component represents the elastic distortion of the crystal lattice structure. Young's modulus is often alluded to as a measure of that deformation. It is 9-10 GPa for freshwater ice, but varies with temperature and grain structure [99]. If specimen loading is fast enough, the resulting elastic response is comparable to that obtained with high-frequency sonic methods [100].





The specimen is loaded at point 1 and unloaded at point 2. E: Effective elastic modulus, D: Delayed elasticity, V: Viscous deformation. Not to scale. Simplified drawing showing the contribution of strain by each component indicated in the figure to the left. E: True elastic modulus, D: Delayed elasticity, V: Viscous deformation. Not to scale.



Close up shown of the right-hand figure above, showing the contribution of the three deformation components. E_x and D_x are the amount of elastic and delayed elastic strain, respectively, at time t_x after load initiation. The viscous response is negligible up to that point.

The viscous component

The viscous component increases immediately upon load application. For short-term scenarios, it is typically very small. This component is the expression of intra-granular deformation mechanisms (generation, motion and rearrangement of crystal defects), which are responsible, for instance, for glacier flow – the slow downward, gravity-driven motion of ice masses in mountains and ice shelves. Viscous deformation under fast loading (seconds to hours) conditions is negligible.

The delayed elastic component

The delayed elastic component does the opposite of the viscous component: it increases rapidly initially and then levels off. This component represents inter-granular sliding, also known as grain boundary sliding (GBS)(Figure below)[101]. During this process, crystal defects are mobilized inside the grain boundary zone. But once the load is removed, the elastic energy stored within the crystals reverses the sliding direction. This form of elasticity is 'delayed' because crystal defects rearrangement requires time.



A simplistic depiction of grain boundary sliding (GBS). Left) An initial, hypothetical grain configuration, with a marker horizon crossing the boundary between grains 1 and 2 (approximate scale). Centre: Loading induces GBS, which generates stress zones inside grains 3 and 4 that counteract sliding. Left: When the load is removed, the stress zones dissipate with time and grain boundary displacement is completely recovered.

Since grain boundary sliding becomes effective immediately upon loading and unloading, it contributes to the elastic – i.e. recoverable – response. Along with the lattice distortion represented by the true elastic (Young's) modulus, the ice stores an additional amount of recoverable strain, which amounts to an 'effective' elastic modulus. Because of the resulting time dependency of the overall elastic response, the analysis of many engineering scenarios involves an effective modulus, which is much lower than the true modulus. The reason is the recoverable strain at any time during loading is the sum of the true elastic strain plus the delayed elastic component. This is the case for the bearing capacity of an ice cover, as pointed out earlier.

Symbol	Explanation
A_T	Inverse of the relaxation time at temperature T
b	Constant = $1/n$
<i>C</i> 1	Constant corresponding to the unit grain size d_1
d	Grain size
d_1	Unit grain size
ε	Viscous (dislocation creep) strain rate for unit stress σ_I
E_T	Young's modulus at temperature T
E_t	'Effective' elastic modulus
n	Stress exponent for dislocation motion induced viscous flow
N	Damage expressed as the number of accumulated cracks
S	Stress exponent for delayed elasticity (~1)
Т	Temperature (K)
t	Time
ε	Total strain
\mathcal{E}_d	Delayed elastic strain
Ee	Elastic strain
\mathcal{E}_{v}	Viscous strain
σ	Applied stress
σ_l	Unit stress

Explanation for the symbols used in some of the equations in this appendix.
Constitutive equations

So far, a short qualitative description of each of the major strain components was provided. Following is a cursory outlook at how each of these components can be obtained, according to the Sinha model.

The total amount of strain recorded by ice under load is the summation of the elastic component, the delayed elastic component and the viscous component (see the Table above for an explanation of the symbols):

$$\varepsilon = \varepsilon_e + \varepsilon_d + \varepsilon_v$$
 Eq. 1

where

$$\varepsilon_e = \frac{\sigma}{E_T}$$
 Eq. 2

$$\varepsilon_d = \frac{c_1 d_1}{d} \left(\frac{\sigma}{E_T}\right)^s \left[1 - exp\left(-(A_T t)^b\right)\right]$$
Eq. 3

$$\varepsilon_{v} = \epsilon \left(\frac{\sigma}{\sigma_{1}}\right)^{n} t$$
 Eq. 4

The elastic strain is time-independent; the delayed elastic strain follows an inverse exponential form; the viscous strain increases linearly with time.

Effective elasticity

When a load is applied onto an ice cover and removed within a relatively short amount of time (say, one minute), a given ice cover sinks and moves back up again. We can assume that, within that time frame, the viscous component is negligible. Assuming s = 1, the total amount of strain is therefore

$$\varepsilon = \frac{\sigma}{E_T} \left\{ 1 + \frac{c_1 d_1}{d} \left[1 - exp\left(-(A_T t)^b \right) \right] \right\}$$
Eq. 5

In a different scenario, where loading is instantaneous (*i.e.* $t \sim 0$)(typically achieved via ultrasonic methods), there would only be an elastic component (ε_e), and Eq. 5 would reduce to Eq. 2. But since, in our scenario, there is a delayed elastic component, the effective elastic response has to take that into account. Keeping in mind that the total strain ε contains both elastic and delayed elastic components, we may define an 'effective elastic modulus' (E_t) as follows

$$E_t = \frac{\sigma}{\varepsilon}$$
 Eq. 6

By combining the two previous equations, we have

$$E_t = \frac{E_T}{1 + \frac{c_1 d_1}{d} [1 - exp(-(A_T t)^b)]} = E_t(t, T, d)$$
 Eq. 7

From here, we can address the frequency response of the effective elastic modulus. Consider an 'average' strain rate (the total strain divided by a given time interval):

$$\epsilon_{av} = \left(\frac{\varepsilon}{t}\right)_{av} = \frac{\sigma}{E_0 t} \left\{ 1 + \frac{c_1 d_1}{d} \left[1 - exp\left(-(A_T t)^b\right) \right] \right\} + \epsilon \left(\frac{\sigma}{\sigma_1}\right)^n t$$
 Eq. 8

Using the two previous equations, it is possible to determine the variation of effective elastic modulus as a function of strain rate for short load durations, so as not to induce a significant amount of viscous strain [102, 103]. The dependency of the effective modulus on frequency of load application is shown in the figure below. In this plot, frequency is assumed to be equal to $(2t)^{-1}$, where *t* is the total time of loading (i.e. equivalent to a full load-unload cycle). The relationship in that figure also varies as a function of other parameters (e.g. ice type, temperature). It is here provided for illustrative purposes. It can be seen that, from loading times of 0.0001 seconds and above, the effective modulus decreases progressively from a value of 9.3 GN/m², the true elastic modulus, to about 5.0 GN/m² for 100 seconds.



The last equation and the figure above illustrate the principle behind the use of an effective modulus, based on a simplified crystal structure. Given the complexity in internal structure of an ice cover, it can conceivably achieve much lower effective moduli, depending on the loading scenario.

Micro-cracking

By definition, a crack is a free surface that forms inside the material. Because the rate of diffusion in ice is low, as mentioned earlier, intragranular plasticity (i.e. crystal deformation) contributes little to the total amount of deformation. Sinha [104, p. 201] points out that, "because of the low diffusivity, the intragranular creep mechanisms in ice contribute relatively less (at the same temperature) to overall deformation than do those in most metals. This makes the contribution of the intergranular mechanisms, such as grain-boundary sliding, more pronounced in ice."

The generation of cracks accelerates deformation. It has been shown [104, 105] that Eq. 4 becomes

$$\varepsilon_{\nu} = \epsilon \left(\frac{\sigma}{\sigma_{1}}\right)^{n} \int_{0}^{t} \left[1 + \left\{\frac{\pi^{2}}{(12\sqrt{3})}\right\} N d^{2} n^{0.5}\right] dt$$
 Eq. 9

At low strain rates ($<10^{-7}s^{-1}$) or a low applied load/stress ($<10^{-4}E_T$), which are conditions that are applicable to glacier flow, micro-cracking does not typically occur. For higher strain rate or stress levels, applicable to bearing capacity scenarios, this mechanism becomes active (figure below) and can ultimately cause the failure of an ice cover.



Top) Polycrystalline ice with micro-cracks [104]. Below) Number of microcracks per unit area observed in ice specimens deformed at -10C submitted to five different stresses [106]

APPENDIX D – WAVE PATTERNS

This appendix contains a reprint of a paper [77] that was published in the proceedings of the Transportation Association of Canada (TAC). It provides evidence of the wave deflections due to moving vehicles on the Tibbitt to Contwoyto Winter Road in the NWT. It also give insights into the notion of 'critical speed' and of required spacing between vehicles.

These patterns are rather unique. The images collected by the TanDEM-X satellites were fortuitous – the satellites' formation flying, which was in a chasing configuration, had other purposes during that mission, totally unrelated with winter roads [76].

Lake Ice Cover Deflection Induced by Moving Vehicles: Comparing Theoretical Results with Satellite Observations

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Abstract

Ice roads are essential to the livelihood of several communities and the operations of several industries in Canada's North. Safe yet maximized exploitation of such roads is paramount to all stakeholders. Through a state-of-the-art remote sensing technology, ice road deformations because of transportation activities over a lake in the Northwest Territories, Canada have been recently measured. In the present paper, the dynamic response of the ice road is theoretically modelled and model results were compared with the remotely-sensed deformations. Comparisons are for two different cases of a slow truck whose motion does not create any significant waves in the ice cover, and a fast truck whose motion creates wave patterns in the ice cover. Remotely-sensed and theoretical deformations, for both cases, compare well. It is then concluded that both the theoretical model and the satellite-derived product could assist in safety and operations improvements of ice roads on lakes. Some preliminary conclusions that may help guide ice road operations are given.

Introduction

Ice roads are an important part of the way of life in the North. They are used to move both people and goods into regions which otherwise would not be accessible in the winter. Ice roads have implications to both an individual's way of life as well as northern industry. For example, ice roads are used to bring in large quantities of food and material to the diamond mines located in the Northwest Territories (NWT) of Canada which otherwise would have to be flown in at much greater expense. The NWT's government, industry and local communities work together to try to ensure safe roads. However, as activities in the North are expected to intensify, and in the context of a warming climate, a decrease in the average number of 'freezing degree-days' means that ice road builders will have to do more with less, i.e. increased activity with a reduced operational lifespan, without compromising the safety of the operations. Various means of counteracting this phenomenon may be envisaged. One is through an improved understanding of ice bearing capacity which may support the optimization of traffic variables including maximum speeds and vehicle interspacing.

In February 2015, two Synthetic Aperture Radar (SAR) satellites comprised in the TanDEM-X mission from the German Aerospace Centre (DLR) and EADS Astrium GmbH (Krieger et al., 2013) imaged the Tibbitt-to-Contwoyto Winter Road (TCWR) in the NWT. Ice cover displacement products obtained

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through analysis of the resulting data were found to display effects of moving vehicles (van der Sanden and Short, 2016). In this paper, we will capitalize on a unique and unprecedented opportunity to compare the information contained in these products with theoretical predictions of the dynamic response of a floating ice plate. A theoretical analysis of this type of loading is followed by comparison and discussion of theoretical ice deflections and displacement patterns measured by TanDEM-X. Some preliminary conclusions that may help guide the operation of the TCWR and others like it will be drawn.

The Tibbit-to-Conwoyto Winter Road (TCWR)

The Tibbitt to Contwoyto winter road begins at Tibbitt Lake at the end of Highway 4 about 60 kilometres east of Yellowknife, Northwest Territories, Canada. From there, it winds its way north linking four diamond mines – Ekati, Diavik, Snap Lake, and finally Tahera at the north end of Contwoyto Lake, Nunavut Territory. The total length of the TCWR is 600 kilometres, about 85% of which is over lake ice. This is a region served by no other highways, and for 10 months of the year it is only accessible by air. The road is open during 8-10 weeks every winter, usually starting by the end of January. The road opens when the ice thickness is about 1.07 m and comprises two to three lanes with a width of about 50 meters each.

TCWR is an important supply line for the mines. Each winter, the TCWR sees between 5,000 and 10,000 truckloads, with gross weight up to 40 metric tons (and sometimes more). Diesel fuel is one of the main items that is trucked up to the mines (www.jvtcwinterroad.ca). Other supplies include cement, tires, ammonium nitrate (for the fabrication of explosives) and various construction materials. There are strict guidelines for the usage of the road (TC WRJV "Winter road regulations and rules of the road," 2015). Notably, the maximum speed for driving on lakes is 25 km/h for loaded trucks and could be up to 60 km/h for unloaded trucks. Also, drivers must maintain 500 m spacing between trucks at all times.

This study focusses on a section of the TCWR on Gordon Lake (Figure 1). Gordon Lake is one of the larger lakes used by the TCWR. It has a maximum length of 45 km, a maximum width of 6.5 km and a maximum depth exceeding 85 m (Moore, 1981).

Remotely-sensed Ice Road Displacements

The capacity of SAR satellites to measure the vertical displacement of ice cover by moving vehicles was explained in van der Sanden and Short (2016). Briefly, this capacity hinges on advanced satellite SAR technology that enables the acquisition of two matching images within seconds for subsequent analysis by means of differential interferometric radar data (DInSAR) processing techniques. For the TanDEM-X data applied in this study, the time lapse between the first acquisition at time T1 and the second at time T2 was 10-seconds. Figure 2 depicts the relationship between, simulated, DInSAR measurements and deflections that may be measured with the help of conventional in situ devices. Definitive numbers regarding the accuracy of DInSAR measurements are hard to give because it depends on the fidelity of an applied external DEM as well as a mix of SAR system and acquisition variables including the operating wavelength, the orbital data quality, the coherence level and the atmosphere's stability. The coherence ranges from 0 to 1 and signifies the quality of the DInSAR measurements. Low and high coherence values denote doubtful and reliable measurements, respectively. Lower coherence values result from temporal change, i.e. from T1 to T2, in the radar reflection characteristics of the object observed. Extending from the results shown in van der Sanden and Short (2016), the accuracy of the satellite

measurements presented in the current paper is estimated to be better than about 1 mm 90% of the time provided the associated coherence is \geq 0.6. DInSAR measurements corresponding to moving vehicles, rather than surrounding unchanging ice cover, are likely to have lower coherence levels and therefore reduced accuracies (down to about 5 mm). The TanDEM-X displacement products utilized for the purpose of this study were geocoded to the UTM WGS84 coordinate system with a pixel spacing of 4 m by 4 m.



Figure 1. (a) Gordon Lake in Northwest Territories, Canada – the locations of the vertical displacement patterns shown in Figures 3 and 7 are marked (b) Vehicles travelling along the TCWR on Gordon Lake (February 2013).



Figure 2. Simulated plots illustrating the use of differential SAR interferometry (DInSAR) to measure ice cover vertical displacements along the travel path of a moving vehicle. The DInSAR measurements equal the superposition of the T2 deflection and the inverse of the T1 deflection. The T1 to T2 time interval is assumed to be 10 seconds. In Figure 2, the moving vehicle responsible for the ice deflection is assumed to be located at a distance of 0 m at T1 and to travel at a speed of 15 m s⁻¹ (van der Sanden and Short, 2016).

Theoretical Modelling of the Steady Response of a Thin Floating Ice Plate Loaded by a Moving Load

This classical mechanics problem has been the topic of several past research works. Here, we briefly review the literature on the coupled solid-fluid mechanics modelling of the problem. For a more detailed literature review, we suggest the book of Squire et al. (1996). Kheysin (1963) was a pioneer to model the underneath fluid as an "actual" fluid rather than an elastic foundation. He studied point and line loads for shallow waters and examined what speeds lead to theoretical deflection singularities. Although original and valuable, his work involved some calculation mistakes. Nevel (1970) corrected Kheysin (1963) work for the point load case and lifted the shallow water condition limitations. He also extended the point load assumption to uniform circular loads. Nevel (1970), however, only calculated ice plate's deflections and stresses under the load center. Davys et al. (1985) studied far-field wave patterns and deflection amplitudes in ice plates loaded by a point load and compared some of their results with deflection measurements of an ice runway at McMurdo Sound, Antarctica. They showed that steady deflection wave will occur only if the speed of the load exceeds the so-called 'critical speed', an important concept in ice road operations. At that stage, and in theory, the deflections will grow with time limitlessly. They showed that the wave patterns in the ice plate strongly depend on the speed of the moving load and that when the speed is very large, no wave exists over a zone behind the load. They named this zone the shadow zone. Milinazzo et al. (1995) lifted the far field limitation of Davys et al. (1985) and also extended the point load limitation of Davys et al. (1985) work by modelling uniformly

distributed loads over rectangular regions. They calculated ice plate deflections everywhere including regions close and far from the load. They also confirmed the existence of a shadow zone behind very fast loads as predicted by Davys et al. (1985) and compared some of their results with the experimental work of Takizawa (1988).

Problem Definition and Formulation

Consider a load moving with a constant velocity on an ice plate floating on a fluid. We now look at the theory for the ice response under these conditions. Doing so, we make some simplifying assumptions:

The plate is assumed to be thin with small deflections relative to its thickness and that:

- 1- The middle plane of the plate does not deform. The middle plane is then neutral which means in-plane external loads can be neglected.
- 2- Planes normal to the neutral plane remain normal to it, which means the resulting shear deflections of the plate can be neglected.
- 3- The normal stresses along the plate thickness are negligible relative to in-plane stresses which means the three-dimensionality of the problem can be neglected, which allows simplification into a two-dimensional problem.

To learn more about the validity conditions of the above assumptions, see Timoshenko and Woinowsky-Krieger (1959).

In addition to the above, we are assuming that the plate is homogeneous and isotropic, behaving linearly elastically and has a uniform thickness.

Moreover, the substrate fluid is assumed to be Newtonian, incompressible, invicid and its flow is assumed to be irrotational. The Euler-Bernoulli's equation could then be used for the fluid dynamics of the problem. The fluid is further assumed to have a uniform density and depth.

Based on the above assumptions, the governing equations of the problem in steady state case in a frame of reference moving with the load are (Nevel 1970; Davys et al. 1985; Milinazzo et. al 1995):

$$D(\eta_{xxxx} + \eta_{yyyy}) - p + \rho_{ice}hu^2\eta_{xx} = -P(x,y)$$
(1a)
$$\phi_{xx} + \phi_{yy} + \phi_{zz} = 0$$
(1b)

$$c + \phi_{yy} + \phi_{zz} = 0 \tag{1b}$$

$$g\eta + \frac{P}{\rho} + u\phi_x|_{z=0} = 0 \tag{1c}$$

$$\dot{\phi}_z|_{z=-H} = 0 \tag{1d}$$

$$\phi_z|_{z=0} = u\eta_x \tag{1e}$$

where η , p, and ϕ are respectively the vertical displacement of the middle plane of the plate (positive when upward), pressure at the water-plate interface, and the fluid velocity potential. ρ_{ice} , ρ , and D are the density of ice, the density of water, and the flexural rigidity of the plate $\left(D = \frac{E\hbar^3}{12(1-\nu^2)}\right)$ where E is the effective Young's modulus, h is the plate thickness, and v is the plate's Poisson's ratio. g, u, and P are the gravitational acceleration, the speed of the moving source and its weight. H is the depth of the fluid and subscripts denote partial differentiation. Note that the above equations are in the Cartesian coordinate system moving with the load along the +x direction and the +z direction is upward.

Equations (1a) through (1c) respectively govern the equilibrium of the plate, conservation of mass of the fluid, and the coupling between the solid and fluid mechanics of the problem. Equations (1d) and (1e) satisfy the conditions of a zero normal-to-lakebed fluid velocity (*z* component), and the equality of the velocity of the fluid and the velocity of the plate at the interface (*z* component). Note that equation (1c) is based on the linearized form of the Euler-Bernoulli's equation and equation (1e) is valid only when the vertical displacement of the plate is small.

The solution of the governing equations could be obtained by the Fourier transform technique:

$$\eta = -\frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{\hat{P}(l,m)}{B(l,m)} e^{-i(lx+my)} dl dm$$
(2a)

$$B(l,m) = Dk^{4} + \rho g - \rho_{ice}hu^{2}l^{2} - \frac{\rho u^{2}l^{2}}{k} coth(kH)$$
(2b)

The details of the solution procedure to obtain equations (2) could be found in Nevel (1970) and Davys et al. (1985).

 $\hat{P}(l,m)$ is the Fourier transform of the load P(x, y) and $k^2 = l^2 + m^2$. *i* is the unit imaginary number. If a steady wave pattern with respect to the moving load exists:

$$ul = \omega$$
 (3)

where ω is the frequency. Equation (3) satisfies the condition that the component of the load velocity normal to any wave crest must be equal to the speed of the wave crest. In this condition the equation B(l, m) = 0 and k are known as the dispersion relation and the wavenumber, respectively.

The phase speed of the present dispersion relation, $\frac{\omega}{k}$, has a global minimum that we denote by c_{min} . No steady disturbance could then travel more slowly than this speed. This means that when the speed of the load is less than c_{min} , no steady waves will exist and disturbances will move away from the load. This c_{min} is usually named the critical speed. Experimentations show that deflections of ice roads are pronounced when the speed of the load approaches c_{min} (Wilson, 1955; 1985), (Sunberg-Falkenmark, 1963), (Beltaos, 1981) and (Takizawa, 1978). The critical speed is found by intersecting the phase speed curve $\frac{\omega(k)}{k}$ ($\omega(k)$ is the frequency as a function of the wavenumber) with the group speed curve $(\frac{d\omega}{dk})$; phase speed and group speed could be found from the dispersion relation. On a day-to-day ice road operation, guidelines use the critical speed concept to limit vehicle speed. In other words, truck drivers are told not to exceed what is thought to be the critical speed, so as to reduce the amount of ice road deflection and the likelihood of ice failure. Such ice failure has been observed to occur as a consequence.

Comparison of Theoretical Ice Deflections and Wave Characteristics with Satellite-derived Data

The theoretical response of TCWR at Gordon Lake is studied in this section. The results of the study are then compared with the satellite-derived data. Two different cases are considered: (1) the response to the motion of a slow heavy northbound truck, and (2) the response to the motion of a fast light southbound truck. Figure 1a showed the location of the trucks on the lake.

Table 1 lists relevant properties of the ice road, loading conditions, and the depth of the lake for each case. Note that for both cases, theoretical results based on two different ice thicknesses are presented. In addition, for the southbound case, theoretical results based on two different effective Young's moduli values are presented. The reasons for these two different thicknesses and effective Young's moduli will be given later in the paper.

		Slow neavy northbound case	Fast light southbound case
	$g,m/s^2$	9.81	
Truck	u, m/s (km/h)	7(25.2)	16(57.6)
	<i>M</i> ,(Mass), <i>kg</i>	40000	20000
lce road	$\rho_{ice}, kg/m^3$	917	
	h, m	1.07 & 1.375	1.07 & 1.375
	ν	1/3	
	E, GPa	5	5 & 7.6
Lake	$\rho, kg/m^3$	1000	
	H, m	17.5	22.5

Table 1. Ice road properties, loading conc	ditions, and the dep	pth of the lake f	or each case.
Slow heavy northh	ound case	Fast light so	uthhound cas

For each case, truck speed, given in Table 1, was estimated based on the distance between the minimum and maximum values of the satellite-derived data in the neighbourhood of the truck. The estimated speed values were corroborated by consulting with TCWR's safety guidelines and authorities (Anonymous, 2015). Typical truck weight for loaded (heavy) and unloaded (light) values obtained from TCWR Joint Venture website (http://www.jvtcwinterroad.ca/) and authorities. A local person experienced in fishing in the area provided the lake depth data which was in part obtained by a depth-measuring device. Although Gordon Lake consists of several islands and rocky shoals, the lake depth is believed to be consistent over a large region in the locations of interest.

Table 2 lists the critical speed values, calculated by a numerical root finding scheme, for the two different locations based on the ice road and lake-related data given in Table 1. For investigated cases, the critical speed does not vary significantly.

Table 2. The critical speed, c_{min} , for the northbound, in curved brackets, and the southbound, shown with bolded font, cases for different effective Young moduli and ice road thicknesses. Note that other parameters affecting the critical speed are given in Table 1.

		h	
		1.07 m	1.375 m
F	5 GPa	13.99 m/s (12.75 m/s)	14.36 m/s (12.91 m/s)
L	7.6 GPa	14.24 m/s	14.51 m/s

The trucks of interest on the TCWR are typically Super B Train trucks (see Fig. 4a) whose trailers are supported by seven axles with four wheels on each axle (two on each side of the truck). Other types of vehicles use this winter road, but for the purpose of this exercise, we assume the patterns observed from the satellite images are from these trucks. We model the moving truck as a concentrated point

load, .i.e., $\widehat{P}(l,m) = -\frac{Mg}{2\pi}$, where *M* is the truck mass. We, however, consider the reality that the truck weight is distributed over all its wheels. We provide more details later.

The case of the slow heavy northbound truck

Figure 3 shows the 10-seconds vertical displacement of the ice road surface for the northbound case derived from the satellite data acquired on February 10th, 2015. The new location of the truck is associated with negative values, visualized by shades of blue, because ice road surface has moved down in this region compared to 10 s earlier. The previous location of the truck is associated with positive values, visualized by shades of red, because the truck surface has moved up within a 10-second interval. No wave pattern is seen for this case which is consistent with the prediction of the theoretical model; the truck speed (7 m/s) is well below the critical speed for this northbound case which is over 12 m/s, as given in Table 2.



-20 -10 0 10 20Figure 3. Satellite-derived 10-seconds vertical displacement of the ice road surface induced by a heavy slow northbound vehicle. The spacing of the overlaid cross grid is 250 m by 250 m.

For the theoretical modelling of the problem, the moving truck is modelled as fourteen moving point loads shown by red circles in Figure 4b. Each of the two back and front trailer axles bear 1/8th of the load while each of the three middle trailer axles bear 1/6th of the load. The truck weight is distributed evenly

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along the y axis. Spacing between axles and the truck width are typical values for the Super B train trucks, (www.richardstransport.com/equipment and www.transportation.alberta.ca/Content/docType281/production/B-train.pdf)



•: The ice road is loaded simultaneously by the truck at these locations

Figure 4. (a) Super B Train (http://www.advanceengineeredproducts.com with permission from AEPL) (b) Schematic of the aerial view of the truck trailers and axles (not to scale).

The deflection of the ice road is given by Equation 2a. The integral is calculated by an iterative numerical method based on a quadrature technique implemented by MATLAB technical computing environment. The integration's absolute and relative tolerances are both 1e-8. The deflection of the central plane, shown in Figure 4b, caused by each of the fourteen moving point loads are superimposed to calculate the total deflection. Figure 5 shows the deflection of the central plane at t = 0 s and at t = 10 s, and also the 10-seconds vertical displacement for two different ice thicknesses. Figure 5 also depicts the 10-seconds vertical displacement based on the satellite data. The satellite-related curve in that figure is extracted on a line connecting the extremums of Figure 3. This line is approximately along the ice road.



Figure 5. The theoretical and satellite-derived displacements of the ice road surface for the northbound case. Two different ice road thicknesses are considered. Satellite data source TanDEM-X, © DLR 2015.

The thickness of the TWCR at Gordon Lake is a function of time. The two considered thickness values of 1.07 m and 1.375 m are early and late season values in the operational period of the road. The date of the satellite data is Feb. 10th, 2015 so the ice road thickness is probably closer to the larger modelled thickness. Note that the variation in the thickness of the lake ice cover as a function of location is probably smaller early in season than it is later in the season. This difference in the variability results from activities such as snow removal and forced flooding that aim to increase ice thickness or repair damages to the road surface. The present theoretical model does not account for this variability in the ice cover's thickness.

The horizontal extent of the downward deflection of the road based on the model and the satellite data are consistent despite the loss of coherence in satellite image in regions alternatingly occupied by a vehicle and ice cover.

Normal in-plane stresses at the bottom of the ice road can be calculated, numerically based on the calculated deflections, by the following equations:

$$\sigma_{xx} = \frac{E}{1 - \nu^2} \frac{h}{2} (\eta_{xx} + \nu \eta_{yy})$$

$$\sigma_{yy} = \frac{E}{1 - \nu^2} \frac{h}{2} (\eta_{yy} + \nu \eta_{xx})$$
(4)

Figure 6a shows the stresses for the two thicknesses. Note that sudden fluctuations in the tail portions of the stress curves in Figure 6a are because of integration noise and need to be ignored. The y component of the normal stress is larger than the x component of the normal stress. This means that when the truck is very heavy, cracks will be along the road rather than across of it. This is supported by the shape of the cracks in Figure 6b that shows an incident happening recently to a loaded moving truck in an ice road near Déline, NWT. The calculated stresses for the northbound case are below the ultimate

tensile strength of ice. The recommended allowed tensile strength in ice roads is between $5 \times 10^5 Pa$ to $7 \times 10^5 Pa$ (Hayley and Proskin, 2008; Masterson, 2009) although the ultimate tensile strength of ice samples in laboratories could be as high as $17 \times 10^5 Pa$ (Timco and O'Brien, 1994). The reason is that this allows for a safety factor of about 3.0 against first crack failure (Masterson, 2009).



Figure 6. (a) The theoretical normal stresses at the bottom of the ice road along the road for two different ice road thicknesses for the northbound case. Fluctuations in tail regions are integration noise and can be overlooked. (b) A recent, March 2016, incident in an ice road near Deline, NWT happening for a loaded moving truck. The circumstances that led to this incident are unknown to the authors as of this writing. The crack shapes suggest that an along-the-road crack has happened before an across-the-road crack. Picture is courtesy of NWT Environment and Natural Resources.

The case of the fast light southbound truck

Figure 7 shows the 10-seconds vertical displacement of the ice road surface for the southbound case derived from satellite data acquired on February 9th, 2015. Wave patterns are obvious in the figure. The theoretical critical speed for this case is 14.51 m/s or lower (depending on ice thickness and effective Young's modulus given in Table 1) while the approximate truck speed is 16 m/s. Since the truck speed is larger than the critical speed, the theoretical model predicts steady wave pattern in the ice cover. This prediction is consistent with the satellite-derived observations shown in Figure 7.





Figure 7. Satellite-derived 10-seconds vertical displacement of the ice road surface for the southbound case. Wave patterns are seen in the figure. The existence of waves is also predicted theoretically since the truck speed is larger than the theoretical critical speed for this case. The spacing of the overlaid cross grid is 500 m by 500 m.

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To compare the theoretically predicted wave patterns and ice deflections with the satellite-derived results, Equations (2a) must be solved. When the speed of the moving load is larger than the critical speed, the integral in Equation (2a) is singular on a closed curved line named the wavenumber curve. Because of this singularity, exact solution of the integral is generally impossible and its numerical treatment is generally much more complex than the case when this singularity is absent. This complexity could be completely avoided if the governing equations of the problem, Equations (1), are directly solved numerically by finite-element, finite-different or similar techniques. We do not seek the direct numerical solution of the governing equations in the present paper. We avoid the complexity of

this integral by seeking asymptotic methods. The limitation of asymptotic methods, however, is its probable invalidity close to the location of the moving load. For details of asymptotic methods see the book of Lighthill (1978). The asymptotic solution for Equation (2a) is (Davys et al. 1985):

$$\eta \approx -\hat{P}(l_0, m_0) \left[\left(\frac{\partial B}{\partial n} \right)_0 \right]^{-1} \left(\frac{2\pi}{|\kappa_0| r} \right)^{0.5} e^{-i(l_0 x + m_0 y + \theta)}$$
(5)

where κ , θ , and r are respectively the curvature of the wavenumber curve in the lm plane, a phase shift factor, and the distance from the moving load, $r^2 = x^2 + y^2$. The phase shift factor is $\pi/4$ if $\kappa \times n_l > 0$ and $3\pi/4$ otherwise. n is the outward unit normal to the wavenumber curve and n_l is the component of n along the l direction. $\frac{\partial B}{\partial n}$ is the directional derivative of the wavenumber curve with respect to n, however, for the calculation of η the sign of this derivative must be changed if $n_l < 0$. Note that the deflection given by the above equation is evaluated at any given point on the wavenumber curve, e.g. point T_0 shown in Figure 8, and a given phase, $K = k_0 \cdot r$. Equation (5) is invalid if T_0 is an inflection point of the wavenumber curve and/or if there is any other location on the curve at which $n = n_{T_0}$. For these two invalid conditions, Equation (5) must be revised; Davys et al. (1985) provides the revised versions. In the present paper, we only evaluate the deflections on the x axis along which Equation (5) is valid. The polar coordinates of constant-phase locations in the xy plane are $\left(\frac{K}{k_0 \cos(\chi)}, \theta\right)$.

Note that Figure 8 is the upper half of the wavenumber curve which is always symmetric with respect to the l axis. The bisection method was used to find many, out of infinity, roots of the dispersion relation.



Figure 8. The upper half of the wavenumber curve for E = 5 GPa and h = 1.07 m and other properties and conditions given in Table 1. The smaller subplot is the wave pattern corresponding to the phase value of $K = \frac{9\pi}{4} rad$.

We have plotted and overlaid theoretical wave patterns on the satellite-derived data in Figure 9. To avoid the complexity of superimposing wave patterns cased by each of the truck wheels, the wave pattern shown in Figure 9 corresponds to a single concentrated moving load when E = 5 GPa and

h = 1.07 m while other properties and conditions are given in Table 1. Note that the theoretical wave patterns show a zone behind the truck over which no wave exists. This is the shadow zone alluded to earlier in this paper, which is also shown in Figure 10 over a larger region on the xy plane. The existence of the shadow zone is theoretically expected when the speed of the moving load exceeds \sqrt{gH} which is the celerity of free surface waves in shallow waters. This is the case for the present southbound case since the truck speed, 16 m/s, is larger than $\sqrt{gH} \approx 14.86$ m/s. A careful investigation of the satellitederived data shown in Figure 7 and/or Figure 9 reveals that the road behind the truck is less disturbed than the road in front of the truck; there is a well defined wave pattern in front of the truck while except one to two distinct wave-like disturbances, the road behind of the truck does not show a high level of disturbance. This supports the existence of the shadow zone.



Figure 9. The comparison of the theoretical wave patterns (black lines) with the satellite-derived wave patterns (Source TanDEM-X, © DLR 2015). Red circle is the probable location of the truck in the satellite-derived data.

Theoretical wave patterns shown in Figure 9 are generally similar to their satellite-derived counterparts both with respect the shape of the waves and wavelengths. The theoretical wavelength and deflection of the road in front of the truck will be compared with satellite-based results later in the paper. Note that the satellite-derived data belong to a 10-seconds long period while the theoretical wave pattern is a snapshot. The authors expect that the satellite-derived and theoretical wave patterns converge for regions far from the truck.



Figure 10. Theoretical wave patterns for E = 5 GPa and h = 1.07 m while other properties and conditions are given in Table 1. Note that the southbound truck is at (0, 0). Waves are not seen over a region behind the truck.

Figure 11 compares the vertical displacement of the road in front of the truck, for properties and conditions for the southbound case given in Table 1, with the satellite-derived displacement. Since the theoretical deflections are based on an asymptotic solution, the deflections calculated are probably incorrect close to the moving source. Applicability of Equation (5) is suggested to be limited to distances more than one to two wavelengths away from the moving load. For the present paper, we calculate the vertical deflection of the road in front of the truck for distances associated with the phase value of $K = \frac{9\pi}{4} rad$ or larger. The theoretical deflection of the road behind the truck is theoretically zero (see shadow zone in Figure 9 and Figure 10). To calculate the theoretical deflections shown in Figure 11, the distribution of the truck weight is modelled similar to the northbound case (the truck weight is distributed over seven locations) except that the truck weight is assumed to be on the central plane shown in Figure 4b.

It is known that the effective Young's modulus of ice depends on the rate at which the ice is loaded (Sinha, 1979; Gold and Sinha, 1980); the higher the loading frequency is, the higher the effective modulus is. For the case when the wavelength is 100 m when the speed is 16 m/s, the loading rate is 0.16 Hz. At this loading rate the effective Young's modulus is approximately 7.6 GPa, for the ice grain size of 3~10 mm. Figure 11 shows the 10-seconds deflections for this higher value of the effective Young's modulus as well as the smaller value of 5 GPa for two different ice thickness values. An increase in either the effective Young's modulus or ice thickness decreases the deflections and increases the wavelength, Figure 11. Among the four modelled combinations of ice thickness and effective Young's modulus, the curve associated with the smallest thickness and modulus overestimates the deflections and underestimates the wavelength. For the other extreme case of the larger ice thickness and modulus, the deflections are underestimated and wavelength is overestimated.

distributed loads over rectangular regions. They calculated ice plate deflections everywhere including regions close and far from the load. They also confirmed the existence of a shadow zone behind very fast loads as predicted by Davys et al. (1985) and compared some of their results with the experimental work of Takizawa (1988).

Problem Definition and Formulation

Consider a load moving with a constant velocity on an ice plate floating on a fluid. We now look at the theory for the ice response under these conditions. Doing so, we make some simplifying assumptions:

The plate is assumed to be thin with small deflections relative to its thickness and that:

- 1- The middle plane of the plate does not deform. The middle plane is then neutral which means in-plane external loads can be neglected.
- 2- Planes normal to the neutral plane remain normal to it, which means the resulting shear deflections of the plate can be neglected.
- 3- The normal stresses along the plate thickness are negligible relative to in-plane stresses which means the three-dimensionality of the problem can be neglected, which allows simplification into a two-dimensional problem.

To learn more about the validity conditions of the above assumptions, see Timoshenko and Woinowsky-Krieger (1959).

In addition to the above, we are assuming that the plate is homogeneous and isotropic, behaving linearly elastically and has a uniform thickness.

Moreover, the substrate fluid is assumed to be Newtonian, incompressible, invicid and its flow is assumed to be irrotational. The Euler-Bernoulli's equation could then be used for the fluid dynamics of the problem. The fluid is further assumed to have a uniform density and depth.

Based on the above assumptions, the governing equations of the problem in steady state case in a frame of reference moving with the load are (Nevel 1970; Davys et al. 1985; Milinazzo et. al 1995):

$$D(\eta_{xxxx} + \eta_{yyyy}) - p + \rho_{ice}hu^2\eta_{xx} = -P(x,y)$$
(1a)
$$\phi_{xx} + \phi_{yy} + \phi_{zz} = 0$$
(1b)

$$c + \phi_{yy} + \phi_{zz} = 0 \tag{1b}$$

$$g\eta + \frac{P}{\rho} + u\phi_x|_{z=0} = 0 \tag{1c}$$

$$\dot{\phi}_z|_{z=-H} = 0 \tag{1d}$$

$$\phi_z|_{z=0} = u\eta_x \tag{1e}$$

where η , p, and ϕ are respectively the vertical displacement of the middle plane of the plate (positive when upward), pressure at the water-plate interface, and the fluid velocity potential. ρ_{ice} , ρ , and D are the density of ice, the density of water, and the flexural rigidity of the plate $\left(D = \frac{E\hbar^3}{12(1-\nu^2)}\right)$ where E is the effective Young's modulus, h is the plate thickness, and v is the plate's Poisson's ratio. g, u, and P are the gravitational acceleration, the speed of the moving source and its weight. H is the depth of the fluid and subscripts denote partial differentiation. Note that the above equations are in the Cartesian coordinate system moving with the load along the +x direction and the +z direction is upward.



Figure 11. The theoretical and satellite-derived displacements of the ice road surface for the southbound case. Two different ice road thicknesses and effective Young's moduli are considered. Satellite data source TanDEM-X, © DLR 2015.

Conclusions and Recommendations for Future Work

The response of the TCWR ice road over Gordon Lake to moving loads was theoretically modelled in the present paper. Ice is modelled as a linearly elastic plate interacting with an underneath inviscid, incompressible fluid. The theoretical 10-seconds vertical displacement of the road was compared with satellite-derived results for two separate cases: 1) a heavy slow truck and 2) a light fast truck. Theory predicts that when the speed of the moving load is higher than a value, named the critical speed, there will be steady waves in the ice road. This prediction was verified by remotely-sensed vertical ice displacements data. Theory also predicts that when the moving load is fast enough, there is a shadow zone behind the load where the ice road is not deflected. Satellite-derived ice displacement data supports this prediction. For the purpose of the present study, a certain number of assumptions were made, leading to uncertainties. Despite these uncertainties and uncertainties in satellite-derived data.

What these analyses seem to indicate is that the speed of southbound vehicles on the TCWR is currently exceeding the critical speed as defined earlier in this paper. They also suggest that load-induced stresses vanish about 100 m away from the vehicle, which, in turn, would indicate the 500 m minimum spacing between vehicles could be reassessed if it is governed by ice strength considerations.

Future efforts to further confirm these results could focus on (1) lowering uncertainties in contributing factors including truck speed, truck weight, ice thickness and lake depth, (2) direct numerical solution of the governing equations to lift the limitation of the presently employed asymptotic method and to enable the prediction of deflections close to the fast moving load, (3) considering the full viscoelastic response, instead of the elastic contribution only, of the ice road to possibly lower the difference between the theoretically predicted displacements and wavelengths for the case of the light fast truck.

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APPENDIX E – Summary of proposed investigations

	Торіс	Proposed investigation
	Physical characterization of winter roads combined with operational dataIf information could be obtained on every winter road operation (over-ice vs over-land, configuration, problem areas,), we would better appreciate which one needs more funding/resource than the other, its logistical capacity, etc.	 Design and development of fully instrumented system that would systematically document gradients, cross-slopes, width, angle of turns, ice thickness, nature of soil, etc. This information would be combined with logistical parameters – opening/closing dates, amount of traffic, nature of goods, etc. <i>Outcome</i>: A full picture of the entire winter road network in any given sector, to guide planning and conduct transportation analytics.
White ice Clear ice	White ice vs clear ice: Difference in strength There is currently little agreement amongst the various guidelines in the country on how to factor in white ice in bearing capacity determination.	 Mechanical testing in a refrigerated basin of fully instrumented layered ice covers up to and beyond failure. Numerical modeling of same, validated against these tests. Outcome – Answer to the following questions: What role does white ice play in the bearing capacity of an ice cover? How should it be factored in ice thickness determination? Should it be at all?
Ice fishing	Static loading – How long can a vehicle remain stationary on an ice cover? Theoretical knowledge on this topic may answer that question, but appropriate guidance has yet to be conveyed in guidelines.	 Micro-crack observation and analysis (visual, acoustic) in laboratory tests and field trials on an instrumented ice cover. Numerical modeling with implementation of known theory, validated against these tests. <i>Outcome</i> – Answer to the following question: How long should a vehicle remain stationary on the ice, as a function of ice cover characteristics and vehicle weight.

Vehicle (red dot) and travel direction	Vehicle speed limit and inter-vehicle distance? A vehicle traveling on floating ice induces a 'wave' pattern in the ice cover, a well-known phenomenon – this increases risks of ice failure. A recent analysis of satellite images suggested current guidelines for speed limit and minimum distance between vehicles could be better optimized.	 Review of past field studies on dynamic loading. Field monitoring of traveling vehicles on a fully instrumented ice cover. Numerical modeling validated against the field observations. <i>Outcome</i> – Updated guidance in determining vehicle speed and intervehicle distance, as a function of ice cover characteristics, vehicle weight and water depth.
Boot for scale	Cracks in the ice cover Cracks (or fissures) naturally occur in all ice covers, but their influence is usually not considered in bearing capacity considerations. Also, crack density may increase as a result of vehicle traffic – this also needs to be investigated.	 Monitoring and quantifying the development of cracks (visual, acoustic) at a target location. Cyclic loading of ice of an ice in a refrigerated basin, also to investigate crack development. Mechanical testing in the laboratory of ice blocks with different crack densities. <i>Outcome</i> – Answer to the following questions: Do cracks in ice matter, and if so, how could they be accounted for in bearing capacity calculations?
	Ice reinforcement technologies Ice reinforcement at vulnerable locations is an effective adaptation measure. With the development of new materials over the last few decades, many new options can be explored.	 Detailed literature review of what ice reinforcement methods have been used so far and how they performed. Review of provincial/territorial regulations on deployment/retrieval. Survey of new technologies and of their applicability to winter roads. Outcome – Promising technologies are identified and plans are made to test them in the field.